HULL IN COMPOSITE, PLYWOOD, AND HIGH DENSITY POLYETHYLENE MATERIALS

NR546 - NOVEMBER 2022

RULE NOTE

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RULES, RULE NOTES AND GUIDANCE NOTES

NR546 DT R04 November 2022 takes precedence over previous revision.

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These rules are provided within the scope of the Bureau Veritas Marine & Offshore General Conditions, enclosed at the end of Part A of NR467, Rules for the Classification of Steel Ships. The current version of these General Conditions is available at the Bureau Veritas Marine & Offshore website.

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November 2022

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Section 1 General Requirements and Calculation Principles

1 General

1.1 Application

1.1.1 General scope of application

The requirements of this Rule Note are applicable to ships having their hull and superstructure totally or partly made of composite materials, plywood or high density polyethylene (HDPE).

The purpose of this Rule Note is to define the general requirements for hull scantling and arrangements, with respect to:

- raw material
- methodology of composite and plywood calculation and of HDPE calculation
- hull structure calculation approach
- classification and /or certification process.

1.1.2 Other applicable Rules

The requirements of this Rule Note apply in addition to the following Society Rules for the classification and/or certification of ships, in particular the requirements concerning:

a) Classification and surveys:
   - NR467, Part A: Rules for the Classification of Steel Ships, Classification and Surveys
   - NR217, Part A: Rules for the Classification of Inland Navigation Vessels, Classification and Surveys
   - NR500, Part A: Rules for the Classification and Certification of Yachts.

b) Loading cases and scantling safety factors:
   - NR600: Hull Structure and Arrangement for the Classification of Cargo Ships less than 65 m and Non Cargo Ships less than 90 m
   - NR500: Rules for the Classification and the Certification of Yachts
   - NR217: Rules for the Classification of Inland Navigation Vessels, Classification and Surveys.

c) Subdivision, compartment and access arrangements and arrangement of hull openings, as applicable:
   - NR600: Hull Structure and Arrangement for the Classification of Cargo Ships less than 65 m and Non Cargo Ships less than 90 m
   - NR566: Hull arrangement, Stability and Systems for ships less than 500 GT
   - NR500: Rules for the Classification and the Certification of Yachts
   - NR217: Rules for the Classification of Inland Navigation Vessels, Classification and Surveys.

Other requirements may be considered by the society in accordance with the service notations and additional service features considered defined in the Part A of the Society Rules listed in item a).

1.1.3 Structural scopes not covered by Rules

The following structural aspects are not covered by the present Rules:

- structure deflection under loads
- structural response to vibrations induced by engines, propeller blades or water jet.

1.1.4 Exceptions

Ships with unusual design, materials, speed or service, or intended to carry special cargoes not provided by the Rules are examined on a case-by-case basis.

1.1.5 Working process and survey at works

Surveys by the Society during ship hull construction within the scope of the classification and/or certification of ships built in unit production or in mass production are defined in Sec 12.

The homologation process of raw materials to grant the hull construction marks ✠ or • within the scope of classification and/or certification is defined in Sec 12.

1.2 Definitions

1.2.1 General

In the present Rule Note, the meaning of the following terms is:

- Laminate: material made from several individual layers. The term laminate is used for panel (hull, superstructure or bulkhead) and for basic stiffener elements (attached plating, web or flange)
- Composite structure: used for panel, secondary or primary stiffeners
- Secondary stiffener: stiffener supporting panels
- Primary stiffener: stiffener supporting secondary stiffeners.

1.2.2 Platform of multihull

A platform of multihull is a strength structure connecting the hulls by primary cross transverse structure elements. These transverse elements may be cross beams or cross bulkheads.

The part of the platform directly exposed to sea effect is designed as platform.

The upper part of the platform and the upper decks are defined as platform deck.

2 Rule Note application

2.1 Hull in composite material

2.1.1 The following steps are to be carried out within the scope of classification and/or certification of ships built in composite materials, from a structural point of view:

- raw materials: certification or equivalent process to grant the hull construction marks ✠ or • (see Sec 12)
- calculation of the theoretical mechanical characteristics of the laminates used for panels and for basic elements of stiffeners (flange, web and attached plating) as defined in Sec 5 (individual layers) and Sec 6 (laminates)
- mechanical sample tests representative of the hull's structure building to compare with the theoretical mechanical characteristics (see Sec 12)
- structure drawings examination
- preliminary survey of the yard and survey at work as defined in Sec 12.

2.1.2 The composite's structure characteristics are directly depending on the type of:

- composites (monolithic or sandwich)
- resin
- fibre
- reinforcement fabric
- hull's manufacturing process.

All these particulars are taken into account in the present Rule Note to characterize the composite materials from a mechanical point of view.

2.1.3 The composite materials considered in this present Rule Note are basically those made from:

- thermoset resin's systems
- glass, carbon or para-aramid based reinforcement fabrics
- manufacturing processes as lay-ups (spray and hand), vacuums (infusion) or pre-pregs.

Composite materials made of other resin's systems, fibres or manufacturing processes may be accepted, provided their specifications are submitted to the Society for approval.

2.2 Hull in plywood material

2.2.1 The following steps are to be carried out within the scope of classification and/or certification of a ship built in plywood, from a structural point of view:

- plywood material certification or equivalent process for the assignment of the hull construction mark ✠ or • (see Sec 9, [2.3])
- structure drawings examination
- preliminary survey of the yard and survey at work as defined in Sec 12.

2.2.2 The plywood's characteristics are directly depending on the timber species, ply number and thickness of each ply.

These particulars are taken into account in the present Rule Note to characterize the plywood material from a mechanical point of view and for hull structure review (see Sec 9).

2.3 Hull in HDPE material

2.3.1 The following steps are to be carried out within the scope of classification and/or certification of a ship built in HDPE, from a structural point of view:

- HDPE material certification or equivalent process for the assignment of the hull construction mark ✠ or • (see Sec 10, [5.1.2])
- structure drawings examination
- preliminary survey of the yard and survey at work as defined in Sec 10, [5.1.1].

3 Calculation principles of hull structure

3.1 General

3.1.1 As a general rule, the review of hull structure is to be carried out under the effect of local loads (pressure and forces directly applied to the individual structural members).

When applicable according to Sec 2, [3.1.1], the review of hull structure is to be also carried out under global hull girder loads (forces and moments which result from effects of local loads acting on the ship as a whole and considered as a beam).

3.1.2 Global hull girder and local strength

As a rule, the global hull girder strength and the local strength are examined independently, as follows:

- the local scantling is examined on the basis of local permissible safety factors defined in relation to the type of local loads applied as defined in Sec 2, [2] and the type of structure element.
- the global scantling of the hull girder and of the platform of multihull is examined as defined in Sec 2, [3], on the basis of a minimum permissible safety factor and a buckling check of elements contributing to the global hull girder strength.

3.1.3 Particular case

A combination between the global hull girder stresses and the local stresses analysis may be carried out as defined in Sec 2, [7] when deemed necessary by the Society (see applicable Society Rules defined in [1.1.2]).

3.2 Calculation principles for panels

3.2.1 General

The scantling of panels are to be checked according to the methodology defined in:

- for composite panel: Sec 6, Tab 1
- for plywood panel: Sec 9, [3]
- for HDPE panel: Sec 10, [3.1]

3.2.2 Panel buckling analysis

When panels are checked under global hull girder loads, a panel buckling analysis is to be carried out.

The two following buckling cases are to be considered:

- panel submitted to compression stress
- panel submitted to shear stress.

The plate panels to be checked under buckling criteria are mainly:

a) Under compression due to longitudinal global loads (hull of monohull and floats of catamaran):
   - bottom and deck panels
   - side shell panels below strength deck and above bottom areas
   - superstructure panels contributing to the longitudinal global strength.

b) Under compression due to transverse global bending of catamaran induced by torsion (primary transverse structure of platform):
   - bottom and deck panels of platform
   - superstructure panels contributing to the transverse global strength.

c) Under shear:
   - side shell panels of monohull and floats of catamarans
   - primary cross transverse structure bulkheads of platform of catamarans.
   - superstructure panels contributing to the longitudinal and transverse global strength.

Other hull areas may be checked under buckling on a case by case basis when deemed necessary by the Society.

3.3 Calculation principles for secondary and primary stiffeners

3.3.1 General

The scantling secondary and primary stiffeners are to be checked according to the methodology defined in: and respectively.

- for composite stiffener: Sec 7, Tab 1
- for plywood stiffener: Sec 9, [4]
- for HDPE stiffener: Sec 10, [3.2]

3.3.2 Stiffener buckling analysis

When continuous stiffeners are checked under global hull girder loads, a stiffener buckling analysis is to be carried out.

The continuous stiffeners to be checked under buckling criteria are mainly:

a) Due to longitudinal global loads (hull of monohull and floats of catamaran):
   - bottom and deck stiffeners
   - side shell stiffeners below strength deck and above bottom areas.

b) Due to transverse global bending of catamaran induced by torsion (primary transverse structure of platform):
   - bottom and deck stiffeners of platform.

3.4 Calculation principles for gluing structure connections

3.4.1 General

Gluing structure connections are adhesive joints where structure elements are bonded by placing a layer of adhesive or resin system between the structure elements.

As a rule, adhesive structure connections are examined by direct calculation taking into account the shear force applied to the adhesive joints, the surface of the joint, the gluing joint characteristics defined in Sec 4, [5] and the safety factor defined in Sec 2, [1.3.5].

Where gluing structure connection are submitted to tension or out of plane forces (cleavage, peel...) due to the joint geometry, or where adhesive with shear elongation at break greater than 10% are used, the gluing structure connection is to be examined on a case by case basis.

4 Drawings and documents to be submitted

4.1 General

4.1.1 As a rule, the drawings and documents to be submitted for hull structure review are listed in the Rules for the classification of ships (see [1.1.2]).

Builder's quality systems checking the general production fabrication and process are to be submitted for review (see Sec 12).

4.2 Additional drawings and documents to be submitted for hull built in composite materials

4.2.1 Laminate

Following informations are to be specified on drawings:

- arrangement of the laminates for the various structural elements (thickness, definition of the successive layers of reinforcement specifying for each layer the mass per square meter of reinforcement, the proportion in mass or in volume of reinforcement, the directions of roving and unidirectional reinforcements, the dimension of lap joint between layers)
- direction of the laminates in relation with the ship structure
- details of the connections between various structural elements.

4.2.2 Individual layer

The technical specifications of suppliers with indication of the types, trademarks and references of the resins and gel-coats, reinforcements and core materials are to be specified.

These specifications are to give the following informations:

- for resins:

  system (polyester, vinylester or epoxy), density, Young modulus, shear modulus, Poisson coefficient, breaking strength and elongation at break
- for reinforcements (unidirectional reinforcements, woven rovings, chopped strand mats):

  fibre's quality (type, density and breaking strength, Young modulus and Poisson coefficient in fibre direction and normal to fibre direction), mass per square meter, thickness and, for woven roving, weft-warp distribution

- for core materials:
  type and quality, density, tensile, compression and shear strengths and elasticity moduli.
- for adhesive used for structural joints:
  adhesive system, density, Young modulus, shear modulus, Poisson coefficient, breaking strength and elongation at break in tensile and shear.

4.3 Additional drawings and documents to be submitted for hull built in plywood materials

4.3.1 Additional drawings and documents, as listed as follows, are to be submitted:

- plywood technical specification of the supplier with indication of wood species, bond type, total thickness, plies thicknesses, Young moduli and bending breaking stresses in the two main directions of the panels
- direction of plywood panels in relation with the ship structure
- panel joining and stiffener joining, indicating the structure continuity of strength
- for adhesive used for structural joints:
  adhesive system, density, Young modulus, shear modulus, Poisson coefficient, breaking strength and elongation at break in tensile and shear.

4.4 Additional drawings and documents to be submitted for hull built in HDPE

4.4.1 Additional drawings and documents, as listed as follows, are to be submitted:

- HDPE technical specification of the supplier
- panel joining and stiffener joining, indicating the structure continuity of strength
- weld specification as defined in Sec 10, [4].

Section 2 Scantling Criteria and Hull Strength Analysis

Symbols

C_V : Rule partial safety factor taking into account the ageing effect on the laminates

C_F : Rule partial safety factor taking into account the fabrication process and the reproducibility of the fabrication, directly linked to the mechanical characteristics of the laminates

C_R : Rule partial safety factor taking into account the type and the direction of main stresses applied to the fibres of the reinforcement fabric of the laminates

C_{CS} : Rule partial safety factor for combined stresses in the individual layers of the laminates

C_i : Rule partial safety factor taking into account the type of loads (sea pressure, dynamic sea pressure or internal pressure)

C_{Buck} : Rule partial safety factor for laminate panel buckling.

1 Hull structure scantling criteria

1.1 General

1.1.1 Scantling criteria for composite structure

The hull structure scantling criteria are based on the calculation principles defined in Sec 1, [3] and safety factors.

The actual safety factors are equal to the ratio between:

- the theoretical breaking stresses of each individual layers of laminates (defined in Sec 5, [5]) or, when applicable, the critical buckling stress of the whole laminate (defined in Sec 6, [4]) or the stiffener (defined in Sec 7, [3.2.2], and
- the actual applied stresses induced by local or global loads.

The actual safety factors are to be greater than the minimum rule safety factors defined in [1.3].

Note 1: Breaking stresses directly deduced from mechanical tests may be taken over from theoretical breaking stresses (see Sec 5, [5.1.3]).

1.1.2 Scantling criteria for plywood structure

The hull structure scantling criteria are defined in Sec 9.

1.1.3 Scantling criteria for HDPE structure

The hull structure scantling criteria are defined in Sec 10.

1.2 Types of stresses considered

1.2.1 The different types of stresses considered to estimate the actual safety factors are:

a) For main stresses analysis in each individual layer ("ply by ply" analysis):
- Main tensile or compressive stresses σ_1 in the longitudinal direction of the fibre, mostly located in:
  - 0° direction of unidirectional tape
  - 0° and 90° directions of woven roving when the set of fibres are interweaved
- Main tensile or compressive stresses σ_2 in the perpendicular direction of the fibre, mostly located in:
  - 90° direction of unidirectional tape or combined fabrics when the set of fibres are stitched together without criss-crossing of fibre
- Main shear stresses parallel to the fibre located in the plane of the individual layer (τ_{12}) and/or between each individual layer (τ_{IL1} and τ_{IL2}, also designated as inter-laminar shear stresses).

b) For combined stress analysis in each individual layer ("ply by ply" analysis):
- combined stresses calculated according to the Hoffman criterion.

c) For buckling analysis in the whole laminate:
- compression stresses in the longitudinal and transverse directions of the panel or structure element
- shear stresses in the plane of the panel or structure element.

1.3 Minimum rule safety factors

1.3.1 General

The minimum rule safety factors are defined in relation with partial safety factors C_V, C_F, C_R, C_i, C_{CS} and C_{Buck}.

These partial safety factors are to be taken equal, at least, to the minimum values defined in the applicable Society Rules for the classification and/or the certification of ships (see Sec 1, [1.1.2]).

1.3.2 Main stresses analysis in individual layers

The minimum rule safety factor SF in each layer is to fulfil the following condition:

$SF \geq C_V \cdot C_F \cdot C_R \cdot C_i$

1.3.3 Combined stresses analysis in individual layers

The minimum rule safety factor SF_{CS}, applicable to the combined stresses in each layer, is to fulfil the following condition:

$SF_{CS} < \Sigma\Phi_{CSiapp}$

where:

$SF_{CS} = C_{CS} . C_V . C_F . C_i$

SF_{CSiapp} : Equal to the positive value of:

$$SF_{CSiapp} = \frac{-b \pm \sqrt{b^2 + 4a}}{2a}$$

with:

$$a = \frac{\sigma_1^{\ 2}}{|\sigma_{brc1}\sigma_{brt1}|} + \frac{\sigma_2^{\ 2}}{|\sigma_{brc2}\sigma_{brc2}|} - \frac{\sigma_1\sigma_2}{|\sigma_{brc1}\sigma_{brt1}|} + \frac{\tau_{12}^{\ 2}}{\tau_{br12}^{\ 2}}$$

$$b = \frac{\sigma_1(|\sigma_{brc1}| - |\sigma_{brt1}|)}{|\sigma_{brc1}\sigma_{brt1}|} + \frac{\sigma_2(|\sigma_{brc2}| - |\sigma_{brt2}|)}{|\sigma_{brc2}\sigma_{brt2}|}$$

σ_i, τ_{12} : Actual stresses, in N/mm², in the considered local ply axis induced by the loading case considered and calculated as defined in Sec 6 for panels and Sec 7 for stiffeners

σ_{bri}, τ_{br12} : Ply theoretical breaking stresses, in N/mm², in the local ply axis, as defined in Sec 5, [5].

Note 1: The combined criterion SF_{CSiapp} is obtained from the following equation:

$$SF_{CSiapp}^{\ 2} \cdot F_{ij} \cdot \sigma_i \cdot \sigma_j + SF_{CSiapp} \cdot F_i \cdot \sigma_i > 1$$

1.3.4 Buckling stresses in the whole laminate

The minimum buckling rule safety factor SF_B, applicable to the whole laminate panel or stiffener is to fulfil the following condition:

$SF_B \geq C_{Buck} \cdot C_F \ . C_V . C_i$

1.3.5 Stress analysis in gluing connection

a) General

As a rule, adhesive structure connections are examined by direct calculation taking into account the shear force applied to the adhesive joints deduced from structure calculation, the surface of the joint, and the gluing joint characteristics determined as defined in Sec 4, [5.2.1]

Where gluing structure connection are submitted to tension or out of plane forces (cleavage, peel...) due to the joint geometry, or where adhesive with shear elongation at break greater than 10% are used, the gluing structure connection is to be examined on a case by case basis.

b) Scantling check

The safety factor equal to the ratio between the theoretical shear breaking stresses of the gluing joint defined in Sec 4, [5.2.1] and the actual applied shear stress in the connection is to fulfil the following conditions:

$SF > 2{,}4\ C_t . C_v . C_F . C_{t°}$ and

$SF > 4$

Where:

C_t : Partial safety factor considered for the shear breaking stress as determined by mechanical tests

C_v : Partial safety factor taking into account the ageing effect

C_F : Partial safety factor taking into account the gluing process and post control process

$C_{t°}$: Partial safety factor taking into account the temperature in service condition

These partial safety factors are to be taken equal, at least, to the minimum values defined in the applicable Society Rules for the classification and/or the certification of ships (see Sec 1, [1.1.2]).

2 Local scantling analysis

2.1 Application

2.1.1 The local scantling of panels, secondary and primary stiffeners is to be reviewed according to the:

- local loads as defined in [2.2]
- rule analysis as defined in Sec 6 for panels and in Sec 7 for stiffeners

- scantling criteria as defined in:
  - [1.3] for laminates
  - Sec 9 for plywood structure
  - Sec 10 for HDPE

2.2 Local loads

2.2.1 General

The rule local loads considered for the structure analysis are the external and internal loads defined in the applicable Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

As a general rule, the different types of local loads to be considered are:

a) Sea pressures:

   These static loads, induced by still water loads and wave loads are considered as uniform on the local structure (these loads are applied to bottom, side, deck and superstructure).

b) Dynamic sea pressures:

   The dynamic sea pressures are loads which have a duration shorter than the period of wave loads and are constituted by:

   - bottom slamming loads: Non-uniform loads on the bottom structures where slamming may occur
   - impact loads on side shell and cross deck of catamaran: These dynamic loads represent a wave impact on side shell and are considered as loads locally distributed on the structure as a column of water of 0,6 m diameter.

Note 1: Side shell primary stiffeners and cross deck primary stiffeners are, as a general rule, examined with sea pressures only, without taking into account the side shell and cross deck impacts.

c) Local internal pressures:

   Local internal pressures are loads induced by liquid cargoes, dry cargoes, accommodations, testing loads and flooding loads.

d) Wheel loads on deck when applicable.

2.2.2 Local load point location

Unless otherwise specified, the local loads are to be calculated:

a) For sea pressures and local internal pressure on:

   - panels: at the lower edge of the panel for monolithic panel, and at the middle of the panels for sandwich panel
   - longitudinal stiffeners: at mid-span of the stiffeners
   - transverse stiffeners: at the lower point (p_{slower}) and at the upper point (p_{supper}) of the stiffeners.

b) For dynamic sea pressures on:

   - panels: at the middle of the panels
   - longitudinal and transverse stiffeners: at mid-span of the stiffeners.

3 Global strength scantling analysis

3.1 Application

3.1.1 Global hull girder longitudinal strength

As a rule, the global hull girder longitudinal strength is to be examined as defined in [4], for monohull ships and for floats of catamarans, in the following cases:

- ships with length greater than 30 m, or
- ships having large openings in decks or significant geometrical structure discontinuity at bottom or deck, or
- ships with a transverse framing system, or
- ships with deck structure made of panels with small thicknesses and stiffeners with large spacings, or
- ships with important deadweight, or
- where deemed appropriate by the Society.

For ship structure built in HDPE, see also Sec 10, [1.2.2]

For ships not covered by the above cases, the hull girder strength is considered satisfied when local scantlings are in accordance with requirements defined in Article [2].

3.1.2 Global transverse strength of catamaran

As a rule, the global transverse strength of catamaran is to be examined as defined in Article [5] for all types of catamaran.

3.1.3 Finite element calculation

The global strength analysis may also be examined on the basis of a 3D finite element model as defined in Article [6].

3.2 Global loads

3.2.1 As a general rule, the different types of global loads to be considered and inducing overall bending moment and shear force acting on the hull and/or platform of catamaran are:

a) Still water loads: the longitudinal distribution of ship lightweight, the weights carried in the ship and the buoyancy, and

b) Wave loads: the distribution of wave loads in head sea and/or quartering sea conditions.

The global still water and waves loads, their combination and the calculation of the overall bending moment considered for the global hull structure rule analysis are defined in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

3.3 Global strength check

3.3.1 General

The global analysis check is to be successively carried out taking into account the minimum rule safety factors based on main stresses and combined stresses in individual layers, and on buckling stresses in the whole laminates (see [1.3]).

The global analysis check is to be carried out for the structure elements contributing to the overall hull girder strength in the following areas of the hull:

- in head sea condition (for monohull and multihull):
  along the ship from 0,30L to 0,7L from the aft end
- in quartering sea and digging in condition (for multihull only):
  along the float from aft to fore end, and in way of each primary transverse cross structure of the platform.

4 Calculation of global strength for monohull ship

4.1 General

4.1.1 Calculation of the hull girder strength characteristics is to be carried out taking into account all longitudinal continuous structural element of the hull.

A superstructure extending over at least 0,4 L may generally be considered as contributing to the longitudinal strength.

The transverse sectional areas of openings such as deck hatches, side shell ports, side shell and superstructure doors and windows in the members contributing to the longitudinal hull girder strength, are to be deduced from the considered transverse section.

Lightening holes, draining holes and single scallops in longitudinal stiffeners need not be deducted if their height is less than 0,25 h_W, without being greater than 75 mm,

where:

h_W : Web height, in mm, of the considered longitudinal.

4.2 Strain and stress in the transverse reference section

4.2.1 Strain and stress in the transverse reference section

The overall strains ε_{Aref} and γ_{Aref}, in%, and stresses σ_{Aref} and τ_{Aref}, in N/mm², in any point of a transverse reference section are obtained from the following formulae:

- Bending:

$$\varepsilon_{Aref} = \frac{M_V}{Z_{Aref} \cdot E_{ref}} \cdot 10^{-1}$$

$$\sigma_{Aref} = \frac{E_{ref}}{100} \cdot \varepsilon_{Aref}$$

where:

M_V : Vertical overall longitudinal bending moment of the combination global loads in head sea condition, in kN·m, calculated as indicated in the applicable Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2])

Z_{Aref} : Section modulus calculated for the reference section according to [4.3], in m³

E_{ref} : Arbitrary reference Young modulus value chosen for the transverse section, in N/mm².

- Shear:

$$\gamma_{Aref} = \frac{Q_v S_v V}{I_{yref} \cdot t_{ref} \cdot E_{ref}} \cdot 10^2$$

$$\tau_{Aref} = \frac{E_{ref}}{100} \cdot \gamma_{Aref}$$

where

Q_v : Vertical overall shear force of the combination global loads in head sea condition, in kN, calculated as indicated in the applicable Society Rule for the classification and/or certification of ships (see Sec 1, [1.1.2])

S_v : Vertical section, in m^2, located above the point considered in the section

V : Vertical distance, in m, between the centre of gravity of the vertical section S_v and the centre of gravity of the whole transverse section

E_{ref} : Arbitrary reference Young modulus value chosen for the transverse section, in N/mm^2.

I_{yref} : Moment of inertia of the transverse reference section, in m^4, as defined in [4.3.2]

t_{ref} : Thickness, in mm, as defined in [4.3.1].

4.2.2 Strain and stress in structure element

The overall stresses σ_A and τ_A, in N/mm^2, and strains ε_A and γ_A, in %, in any point of a structure element of a transverse reference section, are obtained from the following formula:

- bending:

$$\sigma_A = \frac{E_i}{100} \cdot \varepsilon_{Aref}$$

$$\varepsilon_A = \frac{\sigma_A}{100 E_i}$$

- shear:

$$\tau_A = \frac{E_i}{100} \cdot \gamma_{Aref}$$

$$\gamma_A = \frac{\tau_A}{100 E_i}$$

where:

E_i : Actual Young modulus of the considered element contributing to the longitudinal strength, in N/mm^2, defined in Sec 6, [2.2.1] for laminate and in Sec 7, [2.2.3] for stiffener

4.2.3 Simplified method for the calculation of the transverse section shear stress

When the inertia of a section is not determined, the shear stress in a section may be calculated as follow:

- the total shear section may be considered as equal to the sum of the vertical sections of:
  - for longitudinal strength analysis: The side shells and longitudinal bulkheads contributing to the global strength of the hull girder
  - for transversal strength analysis of catamaran: The transversal bulkheads contributing to the global strength of the platform
- the shear strain, in %, in the transverse reference section may be taken equal to:

$$\gamma_{Aref} = \frac{Q_v}{S_{Aref} \cdot G_{ref}} \cdot 10^{-1}$$

where:

Q_v : Vertical overall shear force of the combination global loads in head sea condition, in kN, calculated as indicated in the applicable Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2])

S_{Aref} : Total vertical section, in m^2, of the transverse reference section considered, calculated with the arbitrary reference Shear modulus G_{ref} and equivalent thickness of section elements determined as follow:

$$t_{ref} = t_i \cdot \frac{G_i}{G_{ref}}$$

with:

t_i : Actual thickness of the element considered, in mm

G_i : Actual Shear modulus of the element considered, in N/mm^2

G_{ref} : Arbitrary reference Shear modulus value chosen for the total vertical section reference, in mm^2

- The shear stress, in N/mm^2, in any point of a structure element of a transverse section, is obtained from the following formula:

$$\tau_A = \frac{G_{ref}}{100} \cdot \gamma_{Aref}$$

4.3 Strength characteristics of the transverse reference section

4.3.1 Where the members contributing to the longitudinal strength are made in various composite materials, the bending rigidity and the neutral axis of the hull girder transverse sections are to be calculated taking into account the different Young moduli of the longitudinal members.

A transverse reference section inertia of the hull girder is to be calculated, taking into account the different Young moduli of the members, by a modification of the thicknesses t_{ref}, in mm, obtained as follows:

$$t_{ref} = t_i \cdot \frac{E_i}{E_{ref}}$$

where:

t_i : Actual thickness of the element considered, in mm

E_i : Actual Young modulus of the element considered, in N/mm²

E_{ref} : Arbitrary reference Young modulus value chosen for the transverse reference section, in N/mm².

4.3.2 Section modulus

The reference section modulus Z_{Aref}, in any point of a transverse section along the hull girder, is given, in m³, by the following formula:

$$Z_{Aref} = \frac{I_{Yref}}{|z - N|}$$

where:

I_{Yref} : Moment of inertia, in m⁴, of the transverse reference section considered, calculated with the arbitrary reference Young modulus E_{ref}, with respect to the horizontal neutral axis

z : Z co-ordinate, in m, of the considered point in the transverse section, above the base line

N : Z co-ordinate, in m, of the centre of gravity of the transverse reference section, above the base line.

4.3.3 Section moduli at bottom and deck

The section moduli at bottom and at deck of the reference section are given, in m³, by the following formulae:

- at bottom:

$$Z_{ABref} = \frac{I_{Yref}}{N}$$

- at deck:

$$Z_{ADref} = \frac{I_{Yref}}{V_D}$$

where:

I_{Yref}, N : Defined in [4.3.2]

V_D : Vertical distance, in m, equal to: $V_D = z_D - N$

z_D : Z co-ordinate, in m, of the deck above the base line.

4.3.4 Midship section moment of inertia

As a rule, the midship section moment of inertia about its horizontal neutral axis is to fulfil the following criteria:

$$\frac{M_v \times L^2_{WL} \times 10^{-3}}{10 \times E_{ref} \times I_{Yref}} \leq 0,003 \times L_{WL}$$

where:

M_v, E_{ref}, I_{Yref}: As defined in [4.2.1] and [4.3.2]

L_{WL} : Waterline length of the ship, in m.

5 Calculation of global strength for multihull

5.1 General

5.1.1 Type of calculation approach for catamaran

The global strength of catamaran is to be examined:

- In head sea condition: according the methodology defined in Article [4]. The moment of inertia I_{Yref} is to be calculated for only one float. Platform between floats extending over at least 0,4 L is to be considered for the calculation of I_{Yref}. In this case, I_{Yref} is to be calculated with the area b_R and b_{WD} as defined as follow (see also Fig 1):

  b_R : Breadth equal to 10% of the roof longitudinal length

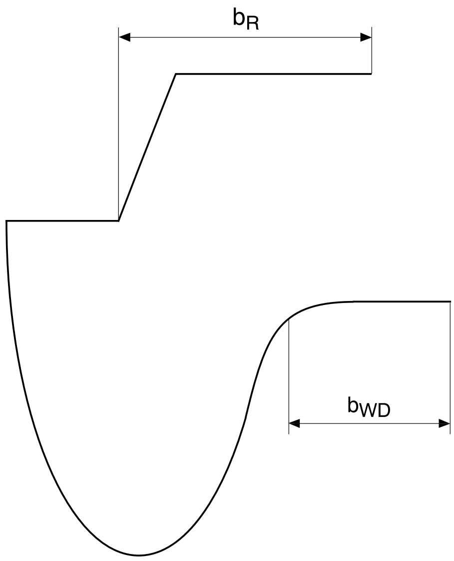
  b_{WD} : Breadth equal to 10% of the cross deck longitudinal length

and,

- In other sea condition: according to [5.2].

The global strength of multihulls having more than two floats are to be examined on a case-by-case basis.

Figure 1 : Hull girder strength area to be taken into account for continuous members (plates and stiffeners)



5.2 Global strength of platform of catamaran

5.2.1 General

The global strength analysis of platform may be carried out by a beam model as defined in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]), taking into account the bending and shear stiffness of the different primary transverse bulkheads (and main beams) and of one float.

The transverses main beams are fixed in way of the inner side shell of the other float.

Any other justified global analysis may be considered.

5.2.2 Main transverse cross deck model

Each resisting transverse member between floats is considered as a beam in the global model, taking into account:

- its bending inertia about an horizontal axis (depending mainly on the web height of the transverse cross beam or bulkhead, the roof deck thickness and the thickness of the underside of the cross deck) calculated according to [4.3]
- its vertical shear inertia (depending on the web height and thickness of the transverse cross beam or bulkhead)
- its span between inner side shells of the floats.

5.2.3 Float model

The float is modelled as a beam having, as far as possible, its:

- vertical and horizontal bending inertia calculated according to [4.3], and
- shear inertia, and
- torsional inertia about longitudinal float axis,

close to the actual float values.

The transverse sections of the float to be considered are to take into account all the longitudinal continuous members (plates and longitudinal stiffeners) in the areas b_R and b_{WD} defined in [5.1.1].

5.2.4 Wave model loading

The vertical and horizontal forces loading the floats and to be considered in the beam model defined in [5.2.1] are defined in the applicable Society Rules for the classification and /or certification of ships (see Sec 1, [1.1.2]).

As a rule, wave in quartering sea condition and digging in wave conditions are to be considered.

5.2.5 Strains and stresses in float and main transverse structure

The overall bending and shear strains ε_{ref} and γ_{ref}, in %, and overall bending and shear stresses σ_{Aref} and τ_{Aref}, in N/mm², are deduced from the beam model calculation in the float and in transverse cross beam and bulkhead.

The stresses in the float and the main transverse structure elements are to be calculated as defined in [4.2.2].

6 Global strength analysis with finite element model

6.1

6.1.1 The global strength analysis may also be examined on the basis of a 3D finite element calculation model submitted by the Designer. As a rule:

a) The model is to be built from:
- a linear calculation approach for the check of the global hull girder longitudinal strength and global transverse strength of catamaran
- linear element or parabolic element for hull structure components (panel, stiffeners…)

Note 1: Non-linear materials may be required for specific components of the global structure (gluing joint with high elongation characteristics, e.g) when deemed necessary by the Society.

Where large openings are provided in side shell and/or in transverse cross bulkhead of catamaran, a special attention is to be paid to ensure a realistic modelling of the bending and shear strengths of the window jambs between windows.

Other calculation approach may be considered by the Society on a case by case basis.

b) Finite element model:

The shell elements mesh are to follow the stiffening system of the modelled hull scantling components considered as far as practicable, hence representing the actual plate panels between local reinforcements. As a rule:
- the size of elements is to be not greater than 100 mm and the aspect ratio of shell elements is generally not to be greater than 2, and in no case greater than 3.
- angles of quadrilateral elements are to be greater than 60° and less than 120°.
- Angles of triangular elements are to be greater than 30° and less than 120°
- The secondary stiffeners may be modelled by rod elements representative of the mechanical characteristics of the stiffeners considered.

c) Document to be submitted

A document setting the hypothesis considered for the calculation model is to be submitted by the Designer for examination. This document is to include:
- a complete representative hull structure model geometry specifying for the different members contributing to the overall strength their main characteristics (materials, mechanical characteristics, scantling)
- the orientation of the shell element co-ordinate system in relation to the reference co-ordinate system of the model and the co-ordinate system of the fibre orientations
- the boundary conditions applied to the model
- the loads distribution induced by global loads
- the reference of the finite element analysis programs used by the Designer
- the mesh size of the highly stressed areas.

7 Global strength and local scantling analysis

7.1 General

7.1.1 When deemed necessary by the Society, the hull scantling may be checked taking into account a combination between the global hull girder and local stresses.

7.1.2 Loads

The loads to be combined are as follow:
- Local loads: sea pressures as defined in [2.2.1], a) and internal loads as defined in [2.2.1], c) with the exception of testing and flooding loads.
- Global loads:
  - for monohull: Still water loads as defined in [3.2.1] a) with wave loads in head sea condition.
  - for multihull: Still water loads with wave loads successively in head sea condition and in quartering sea condition.

Note 1: The global wave loads induced by slamming and/or digging in wave are not to be considered for the check of structure under combination between the global hull girder and local stresses.

7.1.3 Scantling criteria

The rule analysis of panels and stiffeners is to be carried out as defined in Sec 6, [7] and Sec 7, [6] respectively.

The hull structure scantling criteria are defined in Article [1].

7.1.4 Midship section moment of inertia

As a rule, the midship section moment of inertia about its horizontal neutral axis is to fulfil the criteria defined in [4.3.4].

Section 3 Main Structure Arrangements and Special Features

1 General

1.1 Application

1.1.1 The requirements of the present Section apply to longitudinally and transversely framed structure arrangements of ships built in composite materials, plywood or HDPE for:

- structural continuity of hull
- single and double bottoms
- sides and decks
- transverse and longitudinal structures
- superstructures and deckhouses
- special features.

Any other arrangement may be considered on a case-by-case basis.

Additional specific structure arrangements in relation to the service notation of the ship are to comply with the applicable requirements defined in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

1.1.2 Cut-out protections

As a rule, the edges of cut-outs in laminates are to be protected against water and moisture.

2 Structural continuity of hull girder

2.1 General principles for longitudinal hull girder

2.1.1 Attention is to be paid to the structural continuity:

- in way of changes in the framing system
- at the connections of primary and secondary stiffeners.

2.1.2 Longitudinal members contributing to the hull girder longitudinal strength are to extend continuously over a sufficient distance towards the ends of the ship.

Secondary stiffeners contributing to the hull girder longitudinal strength are generally to be continuous when crossing primary supporting members. Otherwise, the detail of connections is considered by the Society on a case-by-case basis.

2.1.3 Where stress concentrations may occur in way of structural discontinuity, adequate compensation and reinforcements are to be provided.

2.1.4 Openings are to be avoided, as far as practicable, in way of highly stressed areas.

Where necessary, the shape of openings is to be specially designed to reduce the stress concentration factors.

Openings are to be generally well rounded with smooth edges.

2.1.5 Primary supporting members are to be arranged in such a way that they ensure adequate continuity of strength. Abrupt changes in height or in cross-section are to be avoided.

2.2 General principles for platform of multihull

2.2.1 Attention is to be paid to the structural continuity of the primary transverse cross structure of the platform ensuring the global transversal resistance of the multihull.

The primary transverse cross structure of catamaran are generally to be continuous when crossing float structures.

The connection between the transverse cross structure of swath and struts are to be examined by direct calculation.

The general continuity principles defined in [2.1] also apply for the primary transverse cross structure of the platform.

3 Subdivision, compartment and access arrangements

3.1 General

3.1.1 Subdivision, compartment and access arrangements are to comply with the applicable requirements defined in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

4 Arrangement of hull openings

4.1 General

4.1.1 Arrangement of hull openings is to comply with the applicable requirements defined in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

5 Bottom structure arrangements

5.1 General arrangement

5.1.1 The bottom structure is to be checked by the Designer to make sure that it withstands the loads resulting from the dry-docking of the ship or the lifting by crane. These loading cases are not within the scope of the classification and/or certification.

5.1.2 Provision is to be made for the free passage of water from all the areas of the bottom to the suctions, by means of scallops in floors and bottom girders.

5.1.3 Additional girders and floors may be fitted in the engine room to ensure adequate rigidity of the structure, according to the recommendations of the engine supplier.

5.1.4 If fitted, solid ballast is to be securely positioned. If necessary, intermediate girders and floors may be required.

5.1.5 Where flanges of floors and girders are at the same level, the web flange of the stiffer member is generally to be continuous. The continuity of the flange of the other member is also to be ensured.

5.1.6 As a rule, bottom girders are to be fitted in way of each line of pillars. If it is not the case, local longitudinal members are to be provided.

5.2 Longitudinal framing arrangement of single bottom

5.2.1 As a general rule, hull with a longitudinally framed single bottom are to be fitted with a continuous or intercostal centre girder.

5.2.2 Where side girders are fitted locally in lieu of the centre girder, they are to be extended over a sufficient distance beyond the ends of the existing centre girder and an additional stiffening of the bottom in the centreline area may be required.

5.2.3 Centre and side girders are to be extended as far as possible towards the ends of the hull.

5.2.4 Longitudinal secondary stiffeners are generally to be continuous when crossing primary members.

Cut-outs fitted in web of floors for the crossing of bottom longitudinals are to be taken into account for shear analysis of floors.

5.3 Transverse framing arrangement of single bottom

5.3.1 In general, the height, in m, of floors at the centreline is to be not be less than B/16. In the case of ships with considerable rise of floor, this height may be required to be increased so as to ensure a satisfactory connection to the frames.

5.3.2 The ends of floors at side are to be located in line with side transverse members.

It may be accepted on a case-by-case basis that floors ends at side be connected on a primary longitudinal member of the side shell or of the bottom.

5.3.3 Openings and cut-outs in web of bottom girders for the crossing of floors are to be taken into account for the girder shear analysis.

5.4 Double bottom arrangement

5.4.1 Double bottom height

As a general rule, the double bottom height is to be:

- sufficient to ensure access to any part of the bottom, and
- not less than 0,76 m in way of the centre girder.

5.4.2 Where the height of the double bottom varies, the variation is generally to be made gradually and over an adequate length; the knuckles of inner bottom plating are to be located in way of floors.

Where such arrangements are not possible, suitable longitudinal structures, such as partial girders, longitudinal brackets etc., fitted across the knuckles are to be fitted.

5.4.3 Adequate continuity is to be provided between double bottom area and single bottom area.

5.4.4 Floors are to be provided:

- watertight in way of transverse watertight bulkheads
- reinforced in way of double bottom steps.

6 Side structure arrangements

6.1 Framing system

6.1.1 In a transverse framing system, structure of sides is made of transverse frames, possibly supported by horizontal stringers.

6.1.2 In a longitudinal framing system, structure of sides is made of longitudinal frames supported by vertical primary supporting members.

6.2 Stiffener arrangements

6.2.1 Secondary stiffeners are normally to be continuous through primary supporting members.

Otherwise, detail of the connection is examined by the Society on a case-by-case basis.

6.2.2 In general, the section modulus of tweendeck frames is to be not less than that required for frames located immediately above.

6.2.3 Transverse web frames and secondary side frames are to be adequately attached to floors and to deck beams.

In general, frames are to be continuous or bracketed to the bottom floors.

Scantlings of the brackets connecting frames to bottom floors and deck beams are to be examined by direct calculation as indicated in Sec 7, [4].

6.3 Openings in the shell plating

6.3.1 Openings in the side shell are to be well rounded at the corners and located, as far as practicable, well clear of superstructure ends.

6.3.2 Large size openings are to be adequately compensated by means of increased lamination. Such compensation is to be partial or total, depending on the stresses occurring in the area of the openings.

6.3.3 Secondary stiffeners cut in way of side shell openings are to be attached to local structural members supported by the continuous adjacent secondary stiffeners or by any other equivalent arrangement.

6.3.4 The laminate of sea chests is generally to be equal to that of the local adjacent shell plating.

6.3.5 Openings for stabilizer fins are considered by the Society on a case-by-case basis.

7 Deck structure arrangements

7.1 General

7.1.1 Adequate continuity of strength (deck laminates and longitudinal stiffeners) is to be ensured in way of:

- stepped strength decks
- changes in the framing system
- large openings.

7.1.2 Deck supporting structures under cranes and windlass are to be adequately stiffened.

7.1.3 Pillars or other supporting structures are generally to be fitted under heavy concentrated loads on decks.

7.1.4 Stiffeners are also to be fitted in way of the ends and corners of deckhouses and partial superstructures.

7.1.5 Beams fitted at deck hatch are to be effectively supported by at least two deck girders located at each side of the deck opening.

7.2 Opening arrangements

7.2.1 The deck openings are to be as much spaced apart as possible.

As practicable, they are to be located as far as possible from the highly stressed deck areas or from the stepped deck areas.

7.2.2 An increase of lamination plate or additional reinforcements may be requested where deck openings are located:

- close to the primary transverse cross structure of platform of multihull
- in areas of deck structural singularity (stepped deck...)
- in way of the fixing of out-fittings.

7.2.3 As a rule, all the deck openings are to be fitted with rounded corners. Generally, the corner radius is to be not less than 5% of the transverse width of the opening.

7.2.4 Corner radiusing, in the case of two or more openings athwart ship in one single transverse section, is considered by the Society on a case-by-case basis.

7.3 Pillar arrangement under deck

7.3.1 Pillars are to be connected to the inner bottom at the intersection of floors and bottom girders, and at deck at the intersection of deck beams and deck girders.

Where it is not the case, an appropriate local structure (partial floors, partial bottom girders, partial deck beams or partial deck girders) is to be fitted to support the pillars.

7.3.2 Local high density core in stiffeners may be required in way where pillars are attached at their heads and heels.

7.3.3 If tensile stress is expected in the pillar, a special attention is to be paid to the connection of the pillar with the structure under tensile loads.

7.3.4 In tanks and in spaces intended for products which procure explosive gases, solid or open section pillars are to be fitted.

7.3.5 Manholes may not be cut in the web of primary structure in way of the head and heel of pillars.

7.3.6 Local structural bulkheads may be considered as pillars, provided that their scantlings comply with Sec 8.

7.3.7 The scantlings of pillars are to comply with the requirements of Sec 8.

7.4 Deck structure in way of lifesaving appliances

7.4.1 The scantling of deck structure supporting launching appliances used for survival craft or rescue boats is to be determined by direct calculations, as defined in the Society Rules for the certification and/or certification of ships (see Sec 1, [1.1.2]).

As a general rule, the minimum rule safety factor applicable to combined stresses SF_{CS}, as defined in Sec 2, [1.3.3], in the primary structure is to be not less than:

$$SF_{CS} \geq 2 \cdot C_V \cdot C_F$$

where:

C_V , C_F : Partial safety factors defined in Sec 2.

7.4.2 The attention is drawn on any possible specific requirement that could be issued by Flag Administration with respect to a structural fire protection.

8 Bulkhead structure arrangements

8.1 General

8.1.1 Bulkheads may be horizontally or vertically stiffened.

Stiffening of horizontally framed bulkheads consists of horizontal secondary stiffeners supported by vertical primary supporting members.

Stiffening of vertically framed bulkheads consists of vertical secondary stiffeners which may be supported by horizontal stringers.

The structural continuity of vertical and horizontal primary supporting members with the surrounding supporting hull structures is to be carefully ensured.

8.1.2 As a general rule, transverse bulkheads are to be stiffened in way of bottom and deck girders, by vertical stiffeners in line with these girders, or by an equivalent system.

Where a deck girder is not continuous, the bulkhead vertical stiffener supporting the end of the deck girder is to be strong enough to sustain the bending moment transmitted by the deck girder.

8.2 Watertight bulkheads

8.2.1 Crossing through watertight transverse bulkheads of bottom, side shell or deck longitudinal stiffeners is to be watertight.

8.2.2 Ends of stiffeners of watertight bulkheads are to aligned with the hull structure members, and are to be fitted with end brackets.

Where this arrangement is made impossible due to hull lines, any other solution may be accepted provided embedding of the bulkhead secondary stiffeners is satisfactorily achieved.

8.2.3 The secondary stiffeners of watertight bulkheads in the tweendecks may be snipped at ends, provided their scantling is increased accordingly.

8.2.4 Watertight doors

The scantling of watertight doors is to be not less than the adjacent bulkhead, taking into account their actual spacing.

Where bulkhead stiffeners are cut in way of watertight door, reinforced stiffeners are to be fitted to support the interrupted stiffeners.

8.3 Non-tight bulkheads

8.3.1 As a rule, non-tight bulkheads not acting as pillars are to be provided with vertical stiffeners being at a maximum:

- 0,9 m apart, for transverse bulkheads
- two frames apart, with a maximum of 1,5m, for longitudinal bulkheads.

8.3.2 Swash bulkheads

As a rule, the total area of openings in a tank swash bulkhead is to be between 10% and 30% of the total area of the swash bulkhead.

8.4 Bulkheads acting as pillars

8.4.1 As a rule, bulkheads acting as pillars (i.e. those designed to sustain the loads transmitted by a deck structure) are to be provided with vertical stiffeners.

8.4.2 A vertical stiffening member is to be fitted on the bulkhead in line with the deck primary supporting member transferring the loads from the deck to the bulkhead and is to be checked according to Sec 8.

8.5 End stiffener connections

8.5.1 Bulkhead stiffener end connections are to be determined by direct calculation taking into account the bending moment and shear force acting on the stiffeners, as defined in Sec 7.

9 Superstructure and deckhouse arrangements

9.1 Superstructure materials

9.1.1 Special attention is to be given to any specific requirements from the Flag Administration about the structural materials and the structural fire protection in the superstructures.

9.2 Connections of superstructures and deckhouses with the hull structure

9.2.1 Superstructure and deckhouse frames are to be fitted, as far as practicable, in way of deck structure and are to be efficiently connected.

Ends of superstructures and deckhouses are to be efficiently supported by bulkheads, diaphragms, webs or pillars.

Where hatchways are fitted close to the ends of superstructures, additional strengthening may be required.

9.2.2 Construction details

The vertical stiffeners of the superstructure and deckhouse walls of the first tier (directly located above the freeboard deck) are to be attached to the decks at their ends.

Efficient connections are to be provided at the lower end and, preferably, at the upper end of the vertical stiffeners of exposed front bulkheads of engine casings and superstructures.

9.2.3 Connection to the hull deck of the corners of superstructures and deckhouses is considered by the Society on a case-by-case basis. Where necessary, local reinforcements may be required.

9.2.4 As a general rule, the side plating at ends of superstructures is to be tapered into the side shell bulwark or the sheerstrake of the strength deck.

Where a raised deck is fitted, the local reinforcement in way of the step is to extend, as a general rule, over at least 3-frame spacings.

9.3 Structural arrangement of superstructures and deckhouses

9.3.1 Superstructures contributing to the hull girder longitudinal strength are to be examined on top of local scantling, taking into account the global strength analysis as defined in Sec 2, [3].

9.3.2 Web frames, transverse partial bulkheads and other equivalent strengthening of each superstructure tier are to be arranged, where practicable, in line with the transverse reinforced structure below.

Web frames are also to be arranged in way of large openings, tender davits, winches, provision cranes and other areas subjected to local loads.

9.3.3 Openings

All the openings in superstructures and deckhouses exposed to greenseas are to be fitted with sills or coamings as defined in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

The attention of the Shipowners, Shipyards and Designer is drawn on the fact that the flag Administration may request application of National Rules.

9.3.4 Sidescutlles, windows and skylights

Sidescuttles, windows and skylights arrangement and scantlings are to be as defined in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

9.3.5 Access and doors

Access openings cut in side plating of enclosed superstructures are to be fitted with doors having a strength equivalent to the strength of the surrounding structure.

Special consideration is to be given to the connection of doors to the surrounding structure.

Securing devices which ensure watertightness are to include tight gaskets, clamping dogs or other similar appliances, and are to be permanently attached to the bulkheads and doors. The doors are to be operable from both sides.

10 Other structures

10.1 Machinery spaces

10.1.1 General

The arrangements of hull structure in the machinery space as regards general strength are to be determined according to the relevant criteria defined in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

It is no substitute to machinery manufacturer's requirements which have to be dealt with at Shipyard diligence.

The Designer may propose arrangements and scantlings alternative to the Society Rules requirements, on the basis of direct calculations which are to be submitted to the Society for examination on a case-by-case basis.

The Society may also require such direct calculations to be carried out whenever deemed necessary.

10.1.2 Seatings of engines

The scantling of seatings of main engines and thrust bearings are to be adequate in relation to the weight and power of engines and the static and dynamic forces transmitted by the propulsive installation.

Transverse and longitudinal members supporting the seatings are to be located in line with floors and bottom girders.

Seatings are to be adequately connected to floors and girders.

10.2 Bulwark

10.2.1 General

The plating and secondary stiffeners are to be checked as defined for side shell in the applicable requirements of the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

The bending moment, in kNm, and the shear force, in kN, to take into account for the scantling check of vertical stays are to be calculated by direct calculation, taking into account the side shell loads defined in the Society Rules for the classification and/or certification of ships, or as defined in [10.2.2].

The analysis of vertical stays is to be carried out as defined for stiffeners in Sec 7, taking into account the safety coefficient in relation with the external load considered.

10.2.2 The bending moment, in kNm, and the shear force, in kN, of stays at their connection to the deck structure in way of the lower part of the bulwark can be obtained by the following formulae:

- Bending moment: The greater value of

  $$M = \frac{p_s s \ell^2}{2}$$

  and:

  - if $\ell \geq 0{,}6$m and $s \geq 0{,}6$m:

    $$M = 0,28 p_{ssmin}(\ell - 0,3)$$

  - if $\ell \geq 0{,}6$m and $s < 0{,}6$m:

    $$M = 0,6 s p_{ssmin}(\ell - 0,3)$$

  - if $\ell < 0{,}6$m:

    $$M = \frac{p_{ssmin} s \ell^2}{2}$$

    with s not taken greater than 0,6m.

- Shear force: The greater value of

  $$T = p_s s \ell$$

  and:

  - if $\ell \geq 0{,}6$m and $s \geq 0{,}6$m:

    $$T = 0,28 p_{ssmin}$$

  - if $\ell \geq 0{,}6$m and $s < 0{,}6$m:

    $$T = 0,6 s p_{ssmin}$$

  - if $\ell < 0{,}6$m:

    $$T = p_{ssmin} s \ell$$

    with s not taken greater than 0,6m.

where:

p_s, p_{ssmin} : Sea pressure and impact pressure on side shell as defined in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2])

s : Spacing of stays, in m

ℓ : Length of stays, in m.

10.3 Helicopter deck and platform

10.3.1 Structure of the helicopter deck located on superstructure weather deck or on platform permanently connected to the hull structure is to be examined according to general arrangement, as applicable, and loading loads as defined in NR600, Ch 5, Sec 3 for ships and NR217, Pt B, Ch 6, Sec 8 for inland navigation vessels.

Where the acceleration at helicopter centre of gravity for upright and inclined ship conditions are not defined by the ship designer, values determined on the basis of NR600 or NR217 are to be taken into account.

Landing area laminates, as well as secondary and primary stiffeners, are to be examined by direct calculations. It is to be checked that the safety factors, defined in Sec 2, [1], are at least equal to the minimum rule safety factors given in the Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]), multiplied by the following coefficients:

- 1,4 for landing area located above accommodation spaces
- 1,15 for landing area located outside a zone covering accommodation spaces
- 1,0 for emergency condition.

Attention is drawn on any possible specific requirement that could be issued by Flag Administration with respect to the structural fire protection and the use of composite materials.

10.4 Hull structure reinforcement for navigation in ice

10.4.1 Application

a) General:

The ice strengthening requirements defined in the present Article are applicable to the hull structure of ships which are assigned one of the following additional class notation:

- **YOUNG ICE 1**
- **YOUNG ICE 2**

The assignment of these additional class notations are subjected to the compliance with NR467, Part A.

b) For inland navigation, the ice strengthening reinforcement are examined on a case by case basis taking into account NR217, Pt D, Ch 2, Sec 1.

10.4.2 Owner's responsibility

It is the responsibility of the Owner to decide which ice class notation is the most suitable in relation to the expected service conditions of the ship.

The ice conditions for the assignment of additional class notation **YOUNG ICE 1** and **YOUNG ICE 2** are defined in NR467, Pt F, Ch 8, Sec 1.

As a guidance, the relation between these additional class notation and the associated ice conditions compatible with the strengthening defined in the present article are as follow:

- young ice (gray or whitish) having a maximum thickness of 30 cm)
- ice concentration:
  - **YOUNG ICE 1**: Open ice (concentration between 6/10 th and 3/10 th)
  - **YOUNG ICE 2**: Very open ice (concentration less than 3/10 th).

10.4.3 General structure scantling

The structure hull areas (longitudinal and vertical) to be strengthened are defined in NR467, Pt F, Ch 8, Sec 2.

The scantling formulae defined in the present Article are based on simply supported hypothesis of the structure element.

10.4.4 Plate scantling

In addition to the analysis of side shell panels carried out in accordance with Sec 6, [5], the panels within the ice belt and subject to ice loads are to be checked according to Sec 6, [5.1.2] taking into account the following values of bending moment, in kN.m/m, and shear force, in kN/m:

a) For transverse framing:

$$M_x = \frac{F_1 p_{PL} s^2}{8} 10^3$$

$$T_{YZ} = \frac{F_1 p_{PL} s}{2} 10^3$$

b) For longitudinal framing:

$$M_y = \frac{p_{PL} h(2s - h)}{8} 10^3$$

$$T_{xz} = \frac{p_{PL} h s}{2 F_2} 10^3$$

where:

F_1 : Coefficient to be taken equal to:

$$F_1 = 1,3 - \frac{4,2}{\left(\frac{h}{s} + 1,8\right)^2} < 1$$

F_2 : Coefficient to be taken equal to:

$$F_2 = 1,4 - \left(0,4\frac{h}{s}\right) > 1$$

h : Height of load area, in m, as defined in NR467, Pt F, Ch 8, Sec 2

s : Spacing, in m, of ordinary or primary stiffeners, as applicable

p_{PL} : Ice pressure on the shell panel, in N/mm², equal to 0,75p

p : Design ice pressure, in N/mm², as defined in NR467, Pt F, Ch 8, Sec 2, [3.2.2] calculated with:

- for **YOUNG ICE 1** C_p= 0,6 and
  for **YOUNG ICE 2** C_p= 0,3
- Nominal ice pressure p_0, in N/mm², equal to 3.

10.4.5 Stiffener scantling

In addition to the analysis of stiffeners carried out in accordance with Sec 7, [4], the stiffeners within the ice belt and subject to ice loads are to be checked according to Sec 7, [4.1.3] taking into account the following values of bending moment, in kN.m, and shear force, in kN:

a) For transverse stiffener:

$$M = \frac{phs(2\ell - h)}{8} 10^3$$

$$T = psh10^3$$

Note 1: Where less than 15% of the span of the stiffener is located within the ice strengthening hull area as defined in [10.4.3], the present check is not required.

b) For longitudinal stiffener:

$$M = \frac{ph\ell^2}{8} 10^3$$

$$T = \frac{ph\ell}{2} 10^3$$

where:

p : Design ice pressure, in N/mm², as defined in [10.4.4].

10.4.6 General structure arrangement

As a general rule, the local reinforcement of the side shell panel in the area of the ice belt and subject to ice loads is to be examined on a case-by-case basis.

In particular, when sandwich panels are used for side shell, designer is to submit the mechanical characteristics and is to justify the scantling of the sandwich to avoid excessive indentation of the sandwich and deterioration of strength and stiffness properties by collapse with the core crushing beneath the ice belt area due to local instability of the compressive face sheets.

Local monolithic side shell panels may be required in the ice belt area.

11 Special features

11.1 Bow doors, bow visors and inner doors

11.1.1 Application and general arrangement

The requirements application and the general arrangement of bow doors, bow visors and inner doors are to be in accordance with the Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

11.1.2 Plate and secondary stiffeners

Scantlings of the plates and secondary stiffeners of bow doors and bow visors are to be not less than scantlings of the plates and secondary stiffeners of hull fore part obtained according to the Society Rules for the classification of ships (see Sec 1, [1.1.2]) and to the general requirements defined in the present Rule Note.

11.1.3 Primary supporting members

Primary supporting member scantlings are to be determined by direct calculation in accordance with the Rules for the classification of ships (see Sec 1, [1.1.2]).

11.1.4 Securing and supporting devices

Securing and supporting devices are to be examined on a case by case by the Society and on the bases defined in [11.1.3].
A particular attention is to be drawn to the connection between metal devices and composite structure.

11.2 Side doors and stern doors

11.2.1 Application and general arrangement

The requirements application and the general arrangement of side doors and stern inner doors are to be in accordance with the Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

11.2.2 Plate and secondary stiffeners

Scantling of the plates and stiffeners of side doors and bow doors are to be not less than scantlings of the adjacent side shell obtained according to the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

11.2.3 Primary supporting members

Primary supporting member scantlings are to be determined by direct calculation in accordance with the Rules for the classification of ships (see Sec 1, [1.1.2]).

11.2.4 Securing and supporting devices

Securing and supporting devices are to be examined on a case by case by the Society and on the bases defined in [11.2.3]. A particular attention is to be drawn to the connection between metal devices and composite structure.

11.3 Hatch covers

11.3.1 General

General arrangement, securing devices, height of coamings and weathertightness where applicable and structure scantling for hatch covers located on exposed or non exposed decks are to be as defined by the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2].

11.4 Rudders

11.4.1 Rudder stock and rudder blade scantlings

Rudder stock and rudder blade scantlings are to be checked by direct calculations, taking into account the forces and torque acting on rudder as defined in the applicable requirements of the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

Where it is not specified otherwise, the safety factors to take into account to check the rudder blade and the rudder stock scantlings are those defined in Sec 2, [1.3], increased by a coefficient to be taken at least equal to 1,3.

11.4.2 Rudder horn and solepiece scantlings

Rudder horn and solepiece scantlings are to be checked by direct calculations, taking into account the forces and torque moments acting on rudder horn or solepiece as defined in the applicable requirements of the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

Where it is not specified otherwise, the safety factors to take into account to check the rudder horn and the solepiece scantlings are those defined in Sec 2, [1.3], increased by a coefficient to be taken at least equal to:

- 1,9 for the main stress safety factor
- 1,3 for the combined stress safety factor.

11.5 Water jet propulsion tunnel

11.5.1 The drawings of water jet ducts, ship supporting structure, thrust bearing, as well as shell openings and local reinforcements, are to be submitted for examination.

The pressure in water jet ducts, the forces and moments induced by the water jet to the ship structure and the calculation procedure from the designer are to be specified.

In no case the scantlings are to be taken less than the requirements defined in:

- the present Rule Note, for the surrounding hull structure
- NR396 Rules for the Classification of High Speed Craft, Ch 3, C3.9.2. In this case, the minimum rule safety factors to take into account for the structure check, as defined in Sec 2, [1.3], are to be the same than those considered for the hull bottom structure.

11.6 Foils and trim supports

11.6.1 Foils and trim tab supports are not covered within the scope of classification and/or certification.

Forces and moments induced by these elements, as well as the designer calculation, are to be submitted for the examination of the surrounding ship structure reinforcements.

As a general rule, attachment structure of foils to the ship structure are to be located within watertight compartments or equivalent.

11.7 Propeller shaft bracket

11.7.1 Propeller shaft bracket scantlings are to be checked by direct calculations, taking into account the forces acting on shaft bracket as defined in the applicable requirements of the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

Where it is not specified otherwise, the safety factors to take into account to check the shaft bracket scantling are those defined in Sec 2, [1.3], increased by a coefficient to be taken at least equal to:

- 1,8 for the main stress safety factor
- 1,5 for the combined stress safety factor.

11.8 Lifting appliances

11.8.1 As a rule, the permanently fixed parts of lifting appliances fitted into the hull, as well as the associated local reinforcements, are considered as integral part of the hull and are to be checked as defined in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

Local reinforcements and hull structure surrounding the crane pedestal are to be checked by direct calculations, taking into account the safety factors defined in Sec 2, [1.3].

11.9 Equipment in chain and anchor

11.9.1 The equipment in anchors and chains is to be as defined in the applicable Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]) in relation of the navigation notation or service notation granted to the ship.

Section 4 Raw Materials for Laminates

1 General

1.1 Application

1.1.1 The mechanical characteristics of laminates used for composite structure depend on raw materials' characteristics.

The present Section gives general informations on the "state of the art" about the main raw materials used for laminates in composite boat building.

1.2 Definitions

1.2.1 The raw materials, used in boat building, are of four main types: resin systems, reinforcements, core materials and adhesives.

1.2.2 Resin systems

Resin systems (or matrix) are thermoset resins (initial liquid, hard and stiff cross linked material that does not return liquid when cured). Resin is used to:

- link reinforcements together
- protect reinforcements from impact, moisture and abrasion
- spread loads through reinforcements' layers.

Resin systems dealt with in this Section are polyester, vinylester and epoxy systems (see Article [2]).

1.2.3 Reinforcements

Reinforcement fabrics are used to improve mechanical characteristics of laminates.

Reinforcement fabrics may be constructed with interlaced yarns or without interlacing, named respectively woven rovings and stitched rovings.

Reinforcement fabrics dealt with in this Section are made of continuous yarns, manufactured with glass, carbon or para-aramid fibres (see Article [3]).

1.2.4 Core materials

Core materials are used in laminate sandwich to improve global moment of inertia of the whole laminate. Sandwich laminates are made of two reinforced faces also named skins, separated by and jointed to a core.

Core materials dealt with in this Section are synthetic foams, natural cores and honeycombs (see Article [4]).

1.2.5 Adhesives

Adhesive materials are generally considered as resin systems and are used to bond together different composite structures or to bond skins to core in sandwich laminates (see Article [5]).

1.2.6 Other raw materials

Other raw materials than those described in [2] to [5] may be considered by the Society on a case by case basis. In this case, the following informations are to be submitted by the manufacturer or the shipyard for examination:

- use restriction of raw materials as defined in [1.3.1]
- values of mechanical characteristics as defined in:
  - for resins and adhesives systems: Tab 1
  - for fibres: Tab 2
  - for core materials: Tab 3
  - for structural adhesives: Article [5]
- methodology or mechanical tests on individual layers to estimate the elastic coefficients (see Sec 5, [3]) and the breaking stresses (see Sec 5, [5]) of the individual layers.

As a rule, raw materials are to be certified as defined in [1.3.2]. However, mechanical tests on laminate panels as defined in Sec 12, [4] and possibly specific mechanical tests on raw materials in order to define the elastic coefficients and breaking stresses may be considered as equivalent to the raw material homologation process.

1.3 Certification of raw materials

1.3.1 Use restriction of raw materials

Raw materials are to be used within the limits given by the manufacturer, taking into account the compatibility between the different materials and the laminating process. In this respect, the Surveyor may ask any useful justification to be submitted, such as:

- technical data sheet of main raw materials (resin, reinforcement fabrics and cores)
- manufacturer statements for raw materials used in naval construction (stability regarding ageing in marine environment, resistance to hydrolysis...)
- type and proportion of catalyst, hardener and accelerator recommended by the manufacturer to be adjusted in the different circumstances of conditions of work (ambient atmosphere, i.e. temperature, relative humidity)
- type approval certificate granted by a recognized Society.

1.3.2 Certification of raw materials

As a general rule, the main raw materials (resins, reinforcement fabrics and cores) used in the laminates for the construction of ships built in composite materials are to be certified within the scope of the classification and/or certification and, in particular, for the assignment of the construction marks ✠ or •.

This process of raw material approval is described in Sec 12, [2].

2 Resin systems

2.1 General

2.1.1 Manufacturing and curing process

As a general rule, thermoset resin systems used in shipbuilding are obtained from a synthetic resin, also named polymer, made of long unsaturated chains of molecules.

The process, which allows to modify the arrangement of molecular chains from free independent chains to a three dimensional linked chains network, is called polymerisation or curing process.

This chemical reaction is observed where resin goes from its liquid state to its solid state. This reaction is accompanied by a heat discharge and is irreversible for thermoset resins.

The three dimensional network is obtained by different curing processes, according to the type of synthetic resins:

- for polyester and vinylester: by mixing synthetic resin with an unsaturated monomer (e.g. styrene) which creates the chemical links. In this case, the chemical reaction needs a catalyst to start the polymerisation process
- for epoxy: by adding a hardener which promotes the polymerisation process. In this case, macromolecules chains are directly linked to each other.

These two different chemical processes have an important effect on mechanical characteristics of the final resin system and particularly on the volumetric shrinkage during the polymerisation (source of stress concentration in the final laminate between resin and fibre).

2.1.2 Glass Transition Temperature (Tg)

The state of polymerisation may be appraised by measuring the “Glass Transition Temperature” (Tg). This is the approximate temperature at which the number of chemical links between molecular chains is significant to change mechanical properties of a cured resin.

The more polymerized is the resin, i.e. the greater is the number of chemical links between macromolecules chains, the higher is the value of Tg.

Where Tg is measured, it is necessary to indicate the reference of the test method, since the measured value of Tg may vary from one method to another.

For epoxy resin systems in particular, Tg may be increased after the resin polymerisation by a post cure with an additional rise of temperature.

2.1.3 Speed of polymerisation

The speed of polymerisation process may be controlled:

- either by the amount of accelerators for polyester and vinylester resin systems, or
- by the amount of a hardener for epoxy resin systems, or
- by a controlled rise of temperature speed.

2.1.4 Resin system reference

The resin systems may be affected by:

- the chemical formulation of polymers used (basic resins, unsaturated monomers, catalysts or hardeners)
- the polymerisation process and the additive products used such as thixotropic or coloured agents.

2.2 Resin system types

2.2.1 Polyester resin systems

Polyester resin systems are the result of mixing unsaturated polyester resin with an unsaturated monomer (also called co-polymer), a catalyst and sometime an accelerator. This reaction is named co-polymerisation.

The functions of these mixed elements are:

- Monomer: the unsaturated monomer, generally styrene, is used to reduce the initial viscosity of the resin before polymerisation and to create the chemical links between chains of polyester macromolecules. The chemical reactive sites, and so the chemical links, are located all along the macromolecules chains of polyester.

  This chemical reaction between polyester and styrene leads to the emission of styrene over, not used in the polymerisation. The global chemical polymerisation is stopped where all the styrene over emission is fully completed or where reactive sites of polyester are fully linked.
- Catalyst: generally of organic peroxide chemical family, the catalyst is used to initiate the reaction between polyester and monomer. It does not take part in the chemical reaction.

  The catalyst proportion and its homogeneous mixing with the polyester/styrene resin before moulding are the main parameters.

  Too low proportion of catalyst may result in an incomplete polymerisation reaction, which may affect the mechanical properties of the final laminate. The catalyst proportion is to be defined by the resin manufacturer.
- Accelerator: an accelerator may also be added to control the chemical speed of reaction, according to the workshop environment (temperature for example).

  Because the accelerator has no influence to initiate the polymerisation reaction, as long as there is no catalyst, it may be directly added by the manufacturer in the polyester resin system. This type of resin is called pre-accelerated.

The polymerisation is carried out at room temperature and goes with an exothermic heat temperature.

The chemical network after polymerisation may be represented by Fig 1.

Two types of polyester resins are used in boat building: orthophtalic and isophtalic.

The mechanical characteristics and the water absorption resistance of isophtalic polyester resin are higher than those of orthophtalic polyester resin. Isophtalic polyester resin is, then, generally used for gelcoats and in the first layers located after the gelcoat.

The main physical characteristics of polyester resin systems are:

- a high volumetric shrinkage during polymerisation due to the great number of chemical links along polyester macromolecules and to styrene emission
- a moderate breaking strain due to the location of chemical links along polyester macromolecules
- a water absorption sensitivity due to ester functions in polyester macromolecules.

Figure 1 : Polyester resin system

```
- P - RS - P - P - RS - P - RS - P -
       |            |       |
       S            S       S
       |            |       |
- P - RS - P - P - RS - RS - RS - P -
```

RS = Reactive site; P = Polyester; S = Styrene

2.2.2 Vinylester resin systems

Vinylester resin systems have the same polymerisation process than polyester systems.

Unsaturated vinylester resin systems differ from polyesters in their chemical structure by:

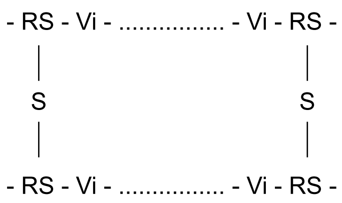
- the location of ester groups and reactive sites at ends of vinylester macromolecules chains
- the lower number of ester groups along chains
- the presence of epoxy groups along the chemical structure.

The chemical network after polymerisation may be represented by Fig 2.

The main physical characteristics of vinylester resin systems are:

- a lower volumetric shrinkage during polymerisation than for polyester systems, due to the lower number of chemical links between macromolecules
- a higher resistance to the water absorption due to the fewer ester functions along macromolecules of vinylester
- higher breaking strain and ductility than for polyester systems due to the location at ends and a fewer number of reactive sites along the macromolecules
- high adhesive characteristics due to the presence, in macromolecules, of polarized molecules able to create non-chemical links (hydrogen type) between macromolecules.

Figure 2 : Vinylester resin system



RS = Reactive site; Vi = Vinylester; S = Styrene

2.2.3 Epoxy resin systems

Epoxy resin systems are made of long macromolecule chains of polymer with epoxy reactive sites located at ends of these chains. Polymerisation of epoxy resin systems may be obtained by:

- mixing epoxy molecular chains with a hardener, generally polyamine or acid anhydride, and/or
- rising curing temperature. In this case, epoxy sites may directly react during the polymerisation between each other, without needing to add a hardener.

One of the two cases here above is necessary to initiate the reaction. In both cases, this chemical reaction is called polyaddition.

Taking into account that epoxy reactive sites do not need a co-polymer to create chemical links between themselves, the quality of a polymerisation may be increased by a second rise of temperature. This process is named post-cure.

The chemical network after polymerisation of polyepoxyde may be represented as shown in Fig 3.

The main characteristics of epoxy resin systems are:

- a low volumetric shrinkage during polymerisation
- a higher breaking strain than polyester and vinylester ones due to the location of the chemical links at macromolecule ends and to the strong resistance of these links
- a high water absorption resistance due to the absence of ester group in the macromolecules
- very high adhesive properties.

Figure 3 : Epoxy resin system

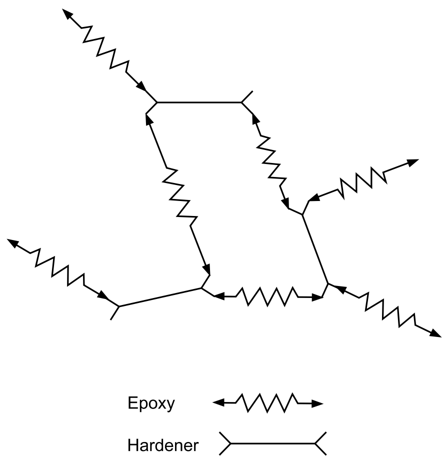


Table 1 : Mechanical characteristics of resins

	Polyester	Vinylester	Epoxy
Density ρ_r	1,20	1,10	1,25
Poisson coefficient ν_r	0,38	0,26	0,39
Tg (°C)	around 60°	around 100°	between 80° and 150° **(1)**
Tensile Young modulus E_r (N/mm²)	3550	3350	3100
Tensile or compression breaking stress (N/mm²)	55	75	75
Tensile or compression breaking strain (%)	1,8	2,2	2,5
Shear modulus G_r (N/mm²)	1350	1400	1500
Shear breaking stress (N/mm²)	around 50	around 65	around 80
Shear breaking strain (%)	3,8	3,7	5,0

(1) The actual value of Tg is depending on the polymerisation process used and, in particular, the temperature used in post-cure.

2.3 Resin mechanical characteristics

2.3.1 General

As a general rule, the resin mechanical characteristics to be taken into account for laminate calculation are to be given by the manufacturer and/or by mechanical tests.

2.3.2 The minimum mechanical characteristics are given in Tab 1, for information.

3 Reinforcements

3.1 General

3.1.1 As a general rule, the reinforcement fibres need to be arranged into fabric products to make handling possible.

These fabrics are textile structures made from continuous yarns, themselves made from an assembly of monofilaments.

In boat building, continuous yarns and monofilaments are generally named “fibres” and fabrics may also be named “rovings”.

The main mechanical characteristics of reinforcement fabrics taken into account in the present Section depend on:

- fibre type
- yarns’ nature
- fabrics’ nature.

3.1.2 After fabrication of monofilaments and/or yarns, a surface treatment, named size, is carried out on yarns in order to:

- create a cohesion between yarns
- improve the quality of the reinforcement/resin interface
- protect the yarns from manufacturing process.

This size plays a very important part to promote fibre/resin interfacial bond strength. In some cases (carbon and para-aramid fibres), size remains on yarns throughout the fabrics’ manufacturing process. In other cases (glass fibre), a first size is applied during yarns’ manufacturing to protect monofilaments and a second one is applied during fabric fabrication to improve fibre/resin interface bonding characteristics.

3.1.3 The linear density of a yarn, expressed in tex (g/km), has a direct influence on the strength of a yarn and then on the final fabric.

3.1.4 Taking into account that a reinforcement may be affected by the nature of fibre, yarn, size or of fabric, the Surveyor may ask that any useful justification, such as technical data sheets of used yarns and/or fabrics, be submitted.

3.2 Fibre types

3.2.1 Glass

Glass monofilaments are obtained by heating a mixture of silica and alumina up to approximately 1600°C, then by stretching the liquid through a die, made up of holes generally of 5 to 25 µm.

They have the same molecular arrangement than glass plates and then are considered as isotropic materials. It means that the mechanical properties are the same in lengthwise and crosswise directions.

The two main types of glass used in composite shipbuilding are the E and R types. E-glass is the reference glass, generally used. R-glass has an higher mechanical resistance due to greater percentages of silica and alumina in its chemical composition.

Glass yarns have a standardized designation (ISO 2078), giving the following information:

- type of glass
- type of monofilament: C for continuous and D for discontinuous, commonly and respectively named strand and staple
- diameter of monofilaments, in µm
- linear density, in tex.

For example, “EC15 800” means E-glass made from continuous monofilaments of 15 µm diameter and 800 tex.

The main physical characteristics of E-glass are:

- good tensile and compression strength and stiffness
- a relatively poor impact resistance.

The main physical characteristics of R-glass are the same as for E-glass, with an improvement of roughly 20% as well as good interlaminar shear strength properties.

3.2.2 Carbon

Carbon monofilaments are mainly made from Poly-AcryloNitril (PAN) precursor fibres.

PAN-precursor fibres are first oxidized (between 200°C and 300°C) and then carbonized under inert atmosphere (between 700°C and 1500°C). These steps rearrange the molecular structure into a network of aromatic carbon layers, which are all chemically linked. This chemical process makes the structure different in the lengthwise direction and in the crosswise direction, which explains the orthotropy of carbon monofilaments.

This first stage of fabrication gives the HS Carbon.

This Carbon may undergo an additional stage, the graphitization (between 2000°C and 3000°C) under inert gas. This final stage increases the number of aromatic carbon layers and chemical links, which give the monofilaments a higher density and a higher Young modulus. Those types of Carbon are named IM and HM Carbon (respectively Intermediate Modulus and High Modulus).

Another type of Carbon, called Pitch Carbon, is also used in shipbuilding. Pitch-precursor carbon monofilaments are obtained by pitch fusion (between 350°C and 450°C), dying and high stretching. Stretching, which is in addition with the chemical process, gives monofilaments a higher anisotropic molecular arrangement than the HM carbon monofilaments then an even higher Young modulus.

Generally, one has to apply a size to carbon monofilaments in order to improve the quality of reinforcement/resin interface and to protect them from the different steps of reinforcements' fabrication.

The industrial designation of carbon multifilament gives, first one the type of carbon, then the number of monofilaments into the multifilament, expressed in thousands of monofilaments (e.g. HR-12k Carbon).

The main characteristics of carbon fibres are:

- very high tensile and compression strength and stiffness
- a very low strength in the normal direction to the fibres' direction
- relatively poor interlaminar shear strength and impact resistance.

3.2.3 Para-aramid

Aramid (Aromatic ether amid) fibres are organic man-made fibres. Para-aramid is the result of a polycondensation of a polyamine and an aromatic acid around 300°C.

Para-aramid monofilaments are obtained successively by hot-dying, cold-water solidification and "high-speed, high-temperature, dry-air" stretching. Stretching, which is a mechanical process, gives to para-aramid monofilaments a very high-oriented molecular organization in the "fibre" direction. Their behaviour and mechanical properties in transverse and "fibre" directions are then very different.

The main characteristics of the para-aramid fibres are:

- a very high impact resistance
- high tensile strength and stiffness and a poor compression strength
- a very poor tensile and compression resistance in transverse direction.

As a general rule, para-aramid are hard to wet by resin systems.

3.2.4 Mechanical characteristics of fibre types

As a general rule, the mechanical characteristics of fibres to be taken into account for laminate calculations are to be submitted by the manufacturer and/or are given by mechanical tests.

The minimum mechanical characteristics are given in Tab 2 for information.

Table 2 : Mechanical properties of fibres

		Glass		Carbon			Para-aramid
		E	R	HS	IM**(1)**	HM**(1)**	
Density ρ_f		2,57	2,52	1,79	1,75	1,88	1,45
Tensile in fibre direction	Poisson coefficient ν_f	0,238	0,20	0,30	0,32	0,35	0,38
	Young modulus $E_{f0°}$ (N/mm^2)	73100	86000	238000	350000	410000	129000
	breaking strain (%)	3,8	4,0	1,5	1,3	0,6	2,2
	breaking stress (N/mm^2)	2750	3450	3600	4500	4700	2850
Tensile normal to fibre direction	Poisson coefficient	0,238	0,20	0,02	0,01	0,01	0,015
	Young modulus $E_{f90°}$ (N/mm^2)	73100	86000	15000	10000	13800	5400
	breaking strain (%)	2,40	2,40	0,90	0,70	0,45	0,70
	breaking stress (N/mm^2)	1750	2000	135	70	60	40
Compression in fibre direction	breaking strain (%)	2,40	2,40	0,90	0,60	0,45	0,40
	breaking stress (N/mm^2)	1750	2000	2140	2100	1850	500
Shear	Modulus G_f (N/mm^2)	30000	34600	50000	35000	27000	12000
	breaking strain (%)	5,6	5,6	2,4	3,0	3,8	4,0
	breaking stress (N/mm^2)	1700	1950	1200	1100	1000	500

(1) Taking into account the large diversity of IM and HM carbons, the values given in this Table are for general guidance only.

3.3 Reinforcement fabrics

3.3.1 General

Usually, reinforcing fibres are arranged into fabric products.

These fabrics may be made by:

- mechanical stitching of fibres (unidirectional fabrics)
- mechanical weaving of fibres (woven fabrics)
- chopped fibres chemically gathered into sheets (mat)
- combined fabrics mixing one or other previous described fabric product
- pre-preg fabrics.

Note 1: Fabrics may be made of different types of fibre, one type of fibre per main fabric direction.

3.3.2 Mechanical characteristics

The mechanical characteristics are influenced by the fibre type used for fabric products, by the direction and positioning of the fibre in the fabric products, and by the various distortion of the fibre induced by weaving process, called waviness.

3.3.3 Unidirectionals (UD)

Unidirectionals are fabrics with fibres in one main direction, gathered by mechanical or chemical stitching, respectively with another fibre or a specific adhesive.

The main characteristics of unidirectionals are:

- high tensile and compression strengths in the fibre direction, due to the high percentage of fibres in fibre direction and also to lack of waviness
- low tensile and compression strengths in the crosswise fibre direction.

From a theoretical point of view, UD are used as reference for the calculations of elastic coefficients of the other fabric types.

3.3.4 Woven Rovings (WR)

Woven rovings are made from two sets of fibre criss-crossing, which form a right angle. The one in the weaving direction is named warp, the other one, weft. Weaving consists in repeating a basic interlace sequence between warp and weft rovings. This sequence is named basic weave.

The four main weave families used in composite shipbuilding are:

- Plains:

  Each weft fibre passes alternatively under and over each warp fibre. This type of fabric is relatively difficult to drape due to its high stability. The fibres are strongly crisscrossed (high waviness)
- Baskets:

  Similar to plains with an alternative pattern made up of two or more weft fibres alternatively interlaced with two or more warp fibres (high waviness)
- Twills:

  One or more weft fibres pass alternatively under two or more warp fibres. The main interests of this fabric type are to make easier the drape process and to limit the bend fibre in the weaving process, as well as to increase the wet operation, named wetting. This is a moderate waviness fabric
- Satins:

  The weaving pattern is obtained by one or more weft fibres crossing several warp fibres and then passing under only one warp fibre. Satins have the same interest as twills, with a lower waviness and a higher wetting ability.

As a general rule, the weaving angle between weft and warp is equal to 90°.

The coefficient “woven balance” Ceq indicates, for each woven roving, the amount of fibres laid in weft and warp directions.

3.3.5 Chopped Strand Mats (CSM)

Chopped strand mats (CSM) are made of fibres chemically gathered to form a web. As fibres are randomly assembled in the web, there is no main direction and CSM are considered as isotropic reinforcements.

CSM may be made of fibres shorter than 50 mm or longer than 50 mm.

As a general rule, only CSM with fibres longer than 50 mm are to be used.

The main characteristics of mats are the nature and the length of fibres, and the area weight.

3.3.6 Combined fabrics

Combined fabrics mainly consist in the assembly by stitching together several reinforcement fabrics, as, for example:

- WR and CSM
- two UD with orientation equal to –45° and +45° to make a fabric named “bi-biais” or “biax”
- three UD with orientation equal to –45°, 0° and +45° to make a “three directional fabric”.
- four UD with orientation equal to –45°, 0°, +45° and 90° to make a “four directional fabric“

3.3.7 Pre-pregs

The pre-pregs consist in reinforcement fabrics (usually UD, WR or combined fabrics) pre-impregnated with a resin system, itself pre-catalysed.

The main advantage of pre-preg fabrics is their accurate resin contents in the reinforcement fabrics.

As a general rule, it is necessary to initiate the polymerisation to activate the chemical reaction by rise in temperature.

3.3.8 Red Cedar

Red cedar is generally used as reinforcement fabric in typical construction, named “strip planking”.

The wood grain orientation is to be taken into account to determine the main characteristics of the laminate panel in its two principle directions.

The main mechanical characteristics of different types of red cedar are given in Tab 5, for general guidance only.

4 Core materials

4.1 General

4.1.1 The aim of a core material in a laminate is to increase the laminate stiffness by increasing its thickness. The core material acts similar to the web of a beam, and so is basically subject to shear forces.

The main characteristics of a core material are low density, shear strength and also capacity to support compression and shear loading without buckling failure.

Three main families are used as core materials:

- foam cores, obtained from expanded synthetic resins
- natural materials, mainly balsa wood
- manufactured materials, such as honeycombs.

4.1.2 The foam materials are to be used within the limits fixed by the manufacturer, in particular for their compatibility with resin and adhesive systems used and working process when rising temperature is provided.

4.1.3 Gluing of core material in sandwich laminate

As a general rule, mechanical tests are to be carried out on sandwich samples representative of hull laminate structure and of gluing process to estimate the final performance of the sandwich laminate, in particular the interface between foam and skins (see Sec 12, [4]).

4.2 Foam cores

4.2.1 General

Foam cores may be manufactured from a large variety of synthetic resins and in a large range of densities and thicknesses.

All the foam cores are to have closed cells to avoid water migration.

The foam cores are to be compatible with resin systems and adhesives used and are to withstand the temperatures for pre-preg or post-cure processes.

Some foam cores need to be heat-treated before use, in order to reduce the gas emitted when they are submitted to temperature rising during laminating process such as post-cure or pre-preg works.

It is to the manufacturer responsibility to define the process of this operation.

The main mechanical characteristics of the most used foam cores in shipbuilding are:

- PVC foam (PolyVinyl Chloride):

  PVC foams are highly resistant to water absorption and to many chemical products, in particular styrene used in polyester and vinylester resin systems.

  There are two different types of PVC foams:

  - the cross linked PVC, and
  - the uncross linked PVC (also named linear PVC).

  The linear PVC foam is more flexible and its mechanical properties are lower than those of the cross linked PVC foam. Cross linked PVC are however more brittle than linear PVC.

- PU foam (Polyurethane):

  As a general rule, PU foams are only used for lightly loaded structures and as frame or girder formers.

  Their mechanical characteristics are relatively low and the interface between foam and skins may be subject to brittleness with ageing.

- PMI foam (Polymethacrylimide):

  The PMI foams are used for their high strength and stiffness. They are also used in construction process requiring temperature rising (pre-pregs for example) due to their high dimensional stability.

- SAN foam (Styrene Acrylo Nitrile):
  The SAN foams are highly resistant to impact loads.
  Their mechanical characteristics are similar to cross linked PVC with higher elongation and toughness.
- PET foam (Polyethylene terephthalate):
  The PET foams are used for their high mechanical properties, compressive strength and high shear modulus. They are also resistant to water and resin absorption due to closed cell structure.
  They are easy to shape by thermoforming.

4.2.2 Mechanical characteristics of foam cores

As a general rule, mechanical characteristics of the foam cores to be taken into account for sandwich calculations are to be given by the manufacturer and/or are given by mechanical tests.

Standard mechanical characteristics of different types of foam cores in relation to their density are given in Tab 3, for information only.

Table 3 : Foams

Foam type	Density (kg/m^3)	Modulus			Poisson coefficient ν_{12} , ν_{21}	Breaking stresses		
		Tensile E_1 , E_2 (N/mm^2)	Compression E_3 (N/mm^2)	Shear G_{12} , G_{13} , G_{23} (N/mm^2)		Tensile σ_1, σ_2 (N/mm^2)	Compression σ_1, σ_2 (N/mm^2)	Shear τ_{12} , τ_{13} , τ_{23} (N/mm^2) **(1)**
Linear PVC	50	21	18	8	0,36	0,7	0,3	0,3
	60	29	28	11	0,31	0,9	0,4	0,5
	70	37	38	14	0,27	1,1	0,6	0,7
	80	44	49	18	0,25	1,3	0,7	0,8
	90	52	59	21	0,24	1,4	0,9	1,0
	100	59	69	24	0,23	1,6	1,0	1,2
	110	67	79	27	0,22	1,8	1,2	1,3
	130	82	99	34	0,21	2,2	1,5	1,7
	140	89	109	37	0,21	2,4	1,6	1,9
Cross linked PVC	50	37	40	18	0,02	1,0	0,6	0,6
	60	47	51	22	0,05	1,4	0,8	0,8
	70	57	63	27	0,07	1,8	1,1	1,0
	80	67	75	31	0,08	2,2	1,4	1,1
	90	78	88	36	0,09	2,5	1,7	1,3
	100	88	102	40	0,10	2,9	1,9	1,5
	110	98	116	44	0,11	3,3	2,2	1,6
	130	118	145	53	0,12	3,9	2,8	2,0
	140	129	161	57	0,12	4,3	3,0	2,2
	170	159	209	71	0,13	5,2	3,8	2,7
	190	180	243	79	0,13	5,8	4,4	3,0
	200	190	260	84	0,13	6,1	4,7	3,2
	250	241	352	105	0,14	7,4	6,0	4,1
SAN	50	52	29	13	0,11	0,9	0,4	0,7
	60	65	37	16	0,18	1,2	0,5	0,8
	70	78	44	18	0,20	1,5	0,6	0,9
	80	92	50	21	0,19	1,7	0,8	1,0
	90	107	55	23	0,17	1,9	0,9	1,1
	100	122	60	26	0,15	2,0	1,1	1,2
	110	137	64	29	0,12	2,2	1,2	1,3
	130	168	71	34	0,06	2,5	1,6	1,5
	140	184	74	36	0,03	2,6	1,8	1,6
	170	234	83	43	0,03	2,9	2,4	1,9
	190	268	88	48	0,03	3,1	2,8	2,1
	200	285	90	51	0,03	3,1	3,0	2,1

(1) τ_{13} and τ_{23} are identical to, respectively, τ_{IL2} and τ_{IL1}.
Note 1: The values given in this Table are for general guidance only.

Foam type	Density (kg/m³)	Modulus			Poisson coefficient ν_{12} , ν_{21}	Breaking stresses		
		Tensile E_1 , E_2 (N/mm²)	Compression E_3 (N/mm²)	Shear G_{12} , G_{13} , G_{23} (N/mm²)		Tensile σ_1, σ_2 (N/mm²)	Compression σ_1, σ_2 (N/mm²)	Shear τ_{12} , τ_{13} , τ_{23} (N/mm²) **(1)**
PET	60	69	35	13	0,32	1,14	0,67	0,43
	70	79	49	15	0,32	1,45	0,84	0,52
	80	89	61	18	0,38	1,72	1,01	0,61
	90	100	74	21	0,38	1,95	1,20	0,70
	100	111	86	24	0,38	2,16	1,39	0,79
	110	121	99	27	0,32	2,36	1,59	0,89
	130	144	122	33	0,27	2,69	2,02	1,09
	150	168	145	40	0,22	3,98	2,47	1,29
	200	230	196	59	0,22	3,55	3,72	1,83
	250	298	241	80	0,12	4,00	5,11	2,39
PMI	50	54	59	21	0,40	1,9	0,8	0,8
	60	69	76	24	0,60	2,1	1,1	1,0
	70	84	94	28	0,60	2,3	1,5	1,2
	80	101	112	33	0,70	2,6	1,9	1,5
	90	119	132	39	0,70	2,9	2,3	1,8
	100	137	152	45	0,70	3,2	2,7	2,1
	110	155	173	52	0,60	3,6	3,2	2,4
	130	195	217	71	0,50	4,5	4,2	3,1
	140	215	239	83	0,40	5,0	4,8	3,5
	170	280	311	131	0,20	6,8	6,7	4,7

(1) τ_{13} and τ_{23} are identical to, respectively, τ_{IL2} and τ_{IL1}.
Note 1: The values given in this Table are for general guidance only.

4.3 Wood cores

4.3.1 General

The mechanical characteristics of wood cores are intrinsically linked to the structure of the wood used.

Two main techniques are used to make sandwich with wood core, which differ in the wood grain orientation in relation to the sandwich plane:

- wood grain running normal to the sandwich plane (balsa). In this case, the wood core behaviour is similar to foams or honeycombs
- wood grain running parallel to the sandwich plane (cedar for example). In this case, in addition to ensuring stiffness and shear resistance of the sandwich, the wood core takes part directly to the global sandwich bending due to significant stiffness.

4.3.2 Balsa

The main mechanical characteristics of balsa are:

- high compression and shear strength
- high stability where heated.

Balsa is available in a large range of densities and thicknesses.

Where balsa with high density and thickness is used, the grain may be transversely solicited by the global sandwich bending.

Standard mechanical characteristics of balsa core materials, in relation to their density, are given in Tab 4 for information.

4.4 Honeycombs

4.4.1 General

Honeycombs are cores whose geometry is described as shown in Fig 4. Honeycomb cores are available in a large range of materials (meta-aramid, thermoplastic resins), cell shape and size thickness. The cell shapes are closely linked to the manufacturing process of the honeycomb.

All these parameters act upon the final mechanical characteristics of the honeycomb core.

Table 4 : Balsa

Main characteristics	Density (kg/m³)								
	80	96	112	128	144	160	176	192	240
Young moduli (N/mm²), parallel to sandwich in-plane E_1 , E_2	23	33	42	51	61	71	80	89	116
Young modulus (N/mm²), normal to sandwich in-plane E_3	1522	2145	2768	3460	4083	4706	5328	5882	7750
Shear moduli (N/mm²), normal to sandwich in-plane G_{13} , G_{23}	57	80	103	127	150	174	197	218	286
Shear modulus (N/mm²), parallel to sandwich in-plane G_{12}	40	55	70	90	105	120	140	150	200
Poisson coefficients ν_{12} , ν_{21}	0,015	0,015	0,015	0,015	0,015	0,015	0,015	0,015	0,015
Breaking compression (N/mm²) normal to sandwich in-plane σ_3	3,53	5,12	5,95	8,17	9,69	11,35	12,80	14,32	18,96
Breaking tensile (N/mm²), parallel to sandwich in-plane σ_1 , σ_2	0,28	0,34	0,42	0,51	0,56	0,64	0,69	0,78	1,00
Breaking compression (N/mm²), parallel to sandwich in-plane σ_1 , σ_2	0,48	0,58	0,71	0,87	0,95	1,10	1,17	1,33	1,70
Breaking shear (N/mm²), through sandwich thickness τ_{13} , τ_{23} **(1)**	0,94	1,10	1,33	1,62	1,73	1,93	2,05	2,33	2,93
Breaking shear (N/mm²), parallel to sandwich in-plane τ_{12}	0,7	0,9	1,2	1,5	1,8	2,0	2,3	2,5	3,4

(1) Breaking shear stresses τ_{IL2} and τ_{IL1} are identical to, respectively, τ_{13} and τ_{23}.
Note 1: The values given in this Table are for general guidance only.

Table 5 : Red cedar

Main characteristics	Density (kg/m³)		
	330	400	460
Young modulus (N/mm²), parallel to grain E_1	7160	8730	10000
Young moduli (N/mm²), perpendicular to grain E_2 , E_3	310	440	560
Shear modulus (N/mm²) G_{12}	620	710	775
Shear modulus (N/mm²) G_{23}	110	160	200
Shear modulus (N/mm²) G_{13}	580	720	850
Poisson coefficient ν_{12}	0,48	0,47	0,47
Poisson coefficient ν_{21}	0,02	0,02	0,03
Breaking tensile (N/mm²), parallel to grain direction σ_1	50	60	70
Breaking tensile (N/mm²), perpendicular to grain direction σ_2	2	2	2
Breaking compression (N/mm²), parallel to grain direction σ_1	28	34	39
Breaking compression (N/mm²), perpendicular to grain direction σ_2	4	5	7
Breaking shear (N/mm²) τ_{12} , $\tau_{13} = \tau_{IL2}$	4	4	4
Breaking shear (N/mm²) $\tau_{23} = \tau_{IL1}$	5	6	7

Note 1: The values given in this Table are for general guidance only.

4.4.2 Thermoplastic honeycombs

The most common polymers used for thermoplastic honeycombs are polyethylen, polycarbonate and polypropylene.

As a general rule, these thermoplastic honeycomb cores have relatively low stiffness and mechanical characteristics and are difficult to bond with the sandwich skins.

The cell shape may be diverse due to the fact that these honeycomb cores are obtained by extrusion process.

The use of thermoplastic honeycombs is submitted to a special examination on a case-by-case basis due to the important diversity of these cores and their temperature sensitiveness.

Special examination is mainly carried out through mechanical tests to estimate the interface and shear resistance of the core in a sandwich construction (see Sec 12).

4.4.3 Meta-aramid honeycombs

The meta-aramid honeycomb cores are obtained from an aramid paper, dipped in resin system.

The density of the aramid paper directly acts upon the shear characteristics while the dip operation in resin acts on the compression characteristics of the honeycomb.

Note 1: Two honeycombs with the same density may differ from a mechanical point of view (shear and compression stresses) in relation to their respective paper thickness and number of dip operations in resin.

Two main cell shapes are available: hexagonal and rectangular. The second shape is being obtained from the hexagonal one with an over expanded mechanical operation.

The main advantage of the rectangular cell shape is its curving ability in the direction L according to Fig 4.

From a mechanical characteristic point of view, the two main particulars of honeycombs are:

- shear characteristics of a honeycomb sheet are different in the two directions
- for a given honeycomb, shear stress depends on its thickness.

Honeycomb cores are mainly used with pre-pregs reinforcement fabrics and need to be heat-treated before use in order to reduce the gas emitted when they are submitted to temperature rising during pre-preg process.

This material, relatively difficult to stick to sandwich skins, is to be dust-free and cleaned before use.

Standard mechanical characteristics of meta-aramid honeycombs in relation to their density, cell size, and thickness are given in Tab 6 for information.

Note 2: The failure modes under tensile and compression stresses along L and W directions, as well as under in-plane shear stresses, are not only dependent on the honeycomb characteristics but also on characteristics of the global sandwich laminates (core thickness and skin characteristics). These failure modes are estimated on a case-by-case by mechanical tests as defined in Sec 12.

Figure 4 : Honeycombs

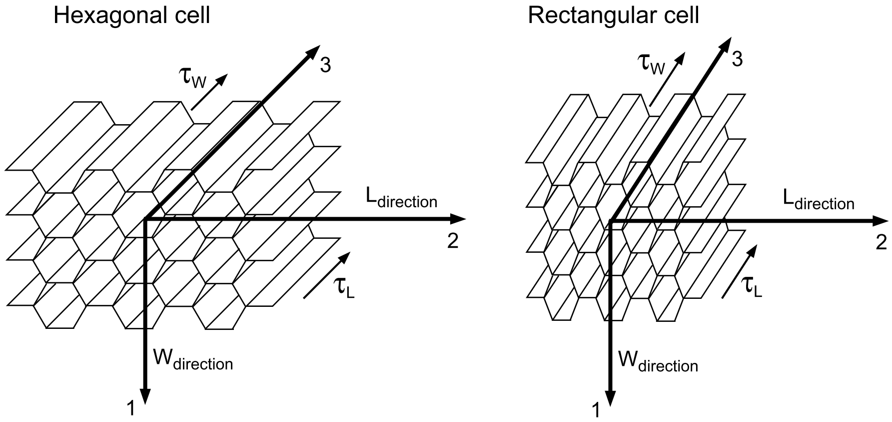


Table 6 : Meta-aramid honeycombs

Density (kg/m³)	Hexagonal								
	E_1 (in W direction)	E_2 (in L direction)	G_{12}	G_{13}	G_{23}	ν_{12}	ν_{21}	τ_{13} (in L direction)**(1)**	τ_{23} (in W direction)**(1)**
48	13,0	16	3,0	37	25	0,82	0,82	1,2	0,70
50	13,6	17	3,3	39	26	0,82	0,82	1,3	0,75
56	14,0	18	4,1	46	30	0,82	0,82	1,5	0,85
64	17,0	20	5,0	59	38	0,82	0,82	1,8	1,00
96	21,0	27	6,0	87	57	0,82	0,82	3,0	1,70

Density (kg/m³)	Rectangular								
	E_1 (in W direction)	E_2 (in L direction)	G_{12}	G_{13}	G_{23}	ν_{12}	ν_{21}	τ_{13} (in L direction)**(1)**	τ_{23} (in W direction)**(1)**
48	105	12,5	1,5	19,0	36,0	0,263	0,263	0,75	0,80
50	108	12,8	1,6	19,5	37,0	0,263	0,263	0,80	0,85
56	114	13,0	1,9	21,0	40,0	0,263	0,263	0,95	0,90
64	135	13,5	2,1	23,5	43,5	0,263	0,263	1,10	1,00
96	180	15,5	3,3	31,0	58,0	0,263	0,263	1,90	1,50

(1) Breaking shear stresses τ_{IL2} and τ_{IL1} are identical to, respectively, τ_{13} and τ_{23}.

Note 1: The values given in this Table are for general guidance only. The mechanical characteristics given by the supplier and taking into account the cell size and paper thickness of the honeycombs are to be taken into account for rules calculations.

5 Structural adhesives

5.1 General

5.1.1 The structural adhesives considered in the present Article are the adhesives used to create a structural connection between:

- two composite structures already cured as, for example, the deck/hull gluing
- one laminate already cured with another laminate not cured as, for example, the stiffener matting-in with the hull
- two raw materials of a laminate as, for example, the gluing of the foam core with the laminate sandwich skin
- two elements of different kinds as, for example, the windows/hull assembly.

5.1.2 The main mechanical characteristics of a structural gluing joint mainly depend on the following parameters:

- resin systems and additives such as thixotropic agents
- type of the components to be bonded as well as their surface preparation (abrasion, cleaning...) and surface treatment
- geometry and thickness of the bonded joint
- curing process of the bonded joint.

5.2 Structural gluing joint characteristics

5.2.1 The large range of adhesive resin systems, curing adhesive process, type of components to be bonded, surface preparation and treatment and the large variety of joint geometry make difficult to define typical mechanical characteristics of gluing joint.

As a rule, the value of the shear breaking stress considered in the present Rule Note is to be taken equal to the minimum value of the:

- initial shear yield stress, in N/mm^2, of the bonding resin specified by the manufacturer, corresponding to the initial yield stress on a substrate equivalent to the examined components, or
- theoretical breaking stress value τ_{IL}, in N/mm^2, of the first layer of the components bonded together.

  Such breaking stress is to be established on a test set up that induce homogeneous shear stress along the bondline, without possibility for stress redistribution.

The shear breaking stress may be determined on the basis of shear stress-strain curve as the intersection of a line tangent to the linear elastic region and a line tangent to the non linear plastic region of the curve (see Fig 5). This curve is to be defined taking into account the maximum air temperature provided in service.

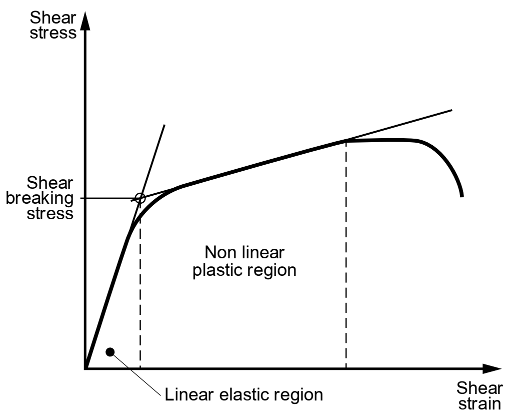
Other values of shear breaking stress deduced from mechanical tests representative of the gluing joint parameters defined in [5.1.2] may be considered by the Society where deemed necessary.

5.2.2 The Society may request that additional mechanical tests (representative of the bonded joints, materials and gluing process), based on the same approach as for the laminate test panel defined in Sec 12, [4], be performed.

5.2.3 Taking into account that significant variations in the mechanical properties of the adhesives occur in relation with temperature, the Society may request that the initial yield stress be determined for different temperature range when the joint is located areas with high temperature (e.g engine room).

5.2.4 When no informations are available, a maximum breaking shear stress from 5 N/mm^2 to 10 N/mm^2 (for high performance bonding) may be considered for the gluing joint.

Figure 5 : Initial yield stress



Section 5 Individual Layers for Laminates

Symbols

C_{eq} : Woven balance coefficient for woven rovings (see [3.2.2]).
$E_{f0°}$: Longitudinal Young modulus of fibre in the axis parallel to the fibre direction, in N/mm^2
$E_{f90°}$: Transverse Young modulus of fibre in the axis perpendicular to the fibre direction, in N/mm^2
E_r : Young modulus of resin, in N/mm^2
e : Individual layer thickness, in mm (see [2.2.1])
G_f : Shear modulus of fibre, in N/mm^2
G_r : Shear modulus of resin, in N/mm^2
ν_f : Poisson coefficient of fibre
ν_r : Poisson coefficient of resin
M_f : Content in mass of fibre in an individual layer, in % (see [2.1.1])
M_r : Content in mass of resin in an individual layer, in % (see [2.1.1])
P_f : Total mass per square meter of dry reinforcement fabric, in g/m^2
ρ_f : Density of fibre
ρ_r : Density of resin
ρ : Density of an individual layer (see [2.3])
V_f : Content in volume of fibre in an individual layer, in % (see [2.1.1])
V_r : Content in volume of resin in an individual layer, in % (see [2.1.1])

1 General

1.1 Application

1.1.1 General

The scantling check of a laminate (based on geometrical characteristics and on plane elastic coefficients of the laminate) is carried out, calculating the safety factors in each layer (except for laminate buckling analysis), as defined in Sec 2, [1.1.1].

The present Section deals with the methodology to determine the theoretical breaking stresses of the individual layers, necessary to calculate the safety factors.

The theoretical breaking stresses considered are:

- in-plane longitudinal tensile and compression breaking stresses
- in-plane transverse tensile and compression breaking stresses
- in-plane shear breaking stress
- interlaminar shear breaking stress.

1.1.2 Methodology

Whatever the type of reinforcement making up the individual layer (CSM, WR or UD), the first step of the methodology consists in estimating the elastic coefficients of an equivalent unidirectional (UD) fabric having the same raw materials and content of fibre as the individual layer to be calculated, according to [3.1].

The elastic coefficients of a woven roving (WR) or a shopped strand mat (CSM) are calculated according to [3.2] and [3.3] respectively, on the basis of the elastic coefficients of the equivalent UD.

The elastic coefficients and breaking stress parameters defined in the present Section are based on the Society experience and take into account the:

- type of raw material (see Sec 4)
- fibre/resin mix ratio, depending on the type of reinforcement and the laminating process
- type of stress in relation to the reinforcement orientation.

1.1.3 Specific methodology

Where unusual individual layers are used, due to specific raw materials as defined in Sec 4, [1.2.6] or laminating process, the Society may request mechanical tests to be performed in order to evaluate elastic coefficients and breaking stresses and compare them to the theoretical approach defined in [3] and [5] respectively.

2 Geometrical and physical properties of an individual layer

2.1 Fibre/resin mix ratios

2.1.1 The fibre/resin mix ratios, which express the amount of fibres and/or resins in an individual layer, may be expressed in:

- mass or volume, and
- resin or reinforcement.

The contents in mass of fibre M_f and in mass of resin M_r are obtained from the following formulae:

M_f = fibre mass (g/m^2) / individual layer mass (g/m^2)

M_r = resin mass (g/m^2) / individual layer mass (g/m^2).

The contents in volume V_f and V_r , and the contents in mass M_f and M_r are deduced from each other by:

$$V_f = \frac{M_f/\rho_f}{M_f/\rho_f + (1 - M_f)/\rho_r}$$

$$V_r = 1 - V_f$$

$$M_f = \frac{V_f \cdot \rho_f}{V_f \cdot \rho_f + (1 - V_f) \cdot \rho_r}$$

$$M_r = 1 - M_f$$

2.1.2 The resin/fibre mix ratios are to be specified by the shipyard and depend on the laminating process.

Common ratio values are given in Tab 1.

Table 1 : Resin/fibre mix ratios (in %)

Laminating process		V_f	M_f		
			Glass	Carbon	Para-aramid
Hand lay-up	CSM	from 15 to 20	from 25 to 35	-	-
	WR	from 25 to 40	from 40 to 60	from 35 to 50	from 30 to 45
	UD	from 40 to 50	from 60 to 70	from 50 to 60	from 45 to 55
Infusion	CSM	30	50	55	50
	WR or UD	45	60		
Pre-pregs		from 55 to 60	from 60 to 70	from 65 to 70	from 60 to 65

2.2 Individual layer thickness

2.2.1 The individual layer thickness, in mm, may be expressed from the fibre content, in mass or in volume, by the following formulae:

$$e = \frac{P_f \cdot \left(\frac{1}{\rho_f} + \frac{1 - M_f}{M_f \cdot \rho_r}\right)}{1000}$$

$$e = \frac{P_f \cdot \left(\frac{1}{V_f \cdot \rho_f}\right)}{1000}$$

2.3 Density of an individual layer

2.3.1 For information, the density of an individual layer is obtained from the following formula:

$$\rho = \rho_f \cdot V_f + \rho_r \cdot (1 - V_f)$$

3 Elastic coefficients of an individual layer

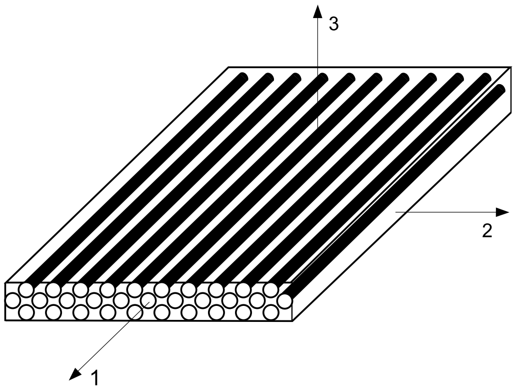
3.1 Unidirectional

3.1.1 Reference axes

The reference axis system for an unidirectional is shown on Fig 1.

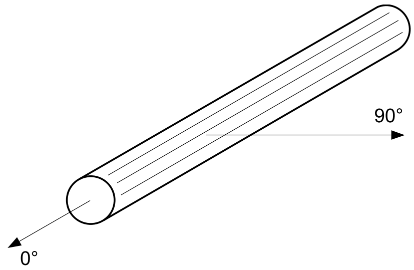
The reference axis system for an elementary fibre is shown on Fig 2.

Figure 1 : Reference axis system for an unidirectional



1 : Axis parallel to the fibre direction
2 : Axis perpendicular to the fibre direction
3 : Axis normal to the plane containing axes 1 and 2, leading to the direct reference axis system.

Figure 2 : Reference axis system of an elementary fibre



0° : Longitudinal axis of the fibre
90° : Transverse axis of the fibre.

3.1.2 Elastic coefficients

The elastic coefficients of an unidirectional are estimated by the following formulae:

- Longitudinal Young modulus E_{UD1} , in N/mm²:

$$E_{UD1} = C_{UD1} \cdot [E_{f0^\circ} \cdot V_f + E_r \cdot (1 - V_f)]$$

- Transverse Young moduli E_{UD2} and E_{UD3} , in N/mm²:

$$E_{UD2} = E_{UD3} = C_{UD2} \cdot \left[\left(\frac{E_r}{1 - \nu_r^2}\right) \cdot \frac{1 + 0,85 \cdot V_f^2}{(1 - V_f)^{1,25} + \frac{E_r}{E_{f90^\circ}} \times \frac{V_f}{1 - \nu_r^2}}\right]$$

- Shear moduli G_{UD12}, G_{UD13} and G_{UD23} , in N/mm²:

$$G_{UD12} = G_{UD13} = C_{UD12} \cdot G_r \cdot \frac{1 + \eta \cdot V_f}{1 - \eta \cdot V_f}$$

$$G_{UD23} = 0,7 \cdot G_{UD12}$$

with $$\eta = \frac{\left(\frac{G_f}{G_r}\right) - 1}{\left(\frac{G_f}{G_r}\right) + 1}$$

- Poisson coefficients:

$$\nu_{UD13} = \nu_{UD12} = C_{UD\nu} \cdot [\nu_f \cdot V_f + \nu_r \cdot (1 - V_f)]$$

$$\nu_{UD21} = \nu_{UD31} = \nu_{UD12} \cdot \frac{E_{UD2}}{E_{UD1}}$$

$$\nu_{UD23} = \nu_{UD32} = C_{UD\nu} \cdot [\nu_f' \cdot V_f + \nu_r \cdot (1 - V_f)]$$

with $$\nu_f' = \nu_f \cdot \frac{E_{f90^\circ}}{E_{f0^\circ}}$$

Coefficients C_{UD1}, C_{UD2}, C_{UD12} and $C_{UD\nu}$ (see Tab 2) are experimental coefficients taking into account the specific characteristics of fibre type.

Table 2 : Coefficients C_{UD1}, C_{UD2}, C_{UD12} and $C_{UD\nu}$

	E-glass	R-Glass	Carbon HS	Carbon IM	Carbon HM	Para-aramid
C_{UD1}	1,0	0,9	1,0	0,85	0,90	0,95
C_{UD2}	0,8	1,2	0,7	0,80	0,85	0,90
C_{UD12}	0,9	1,2	0,9	0,90	1,00	0,55
$C_{UD\nu}$	0,9	0,9	0,8	0,75	0,70	0,90

3.2 Woven roving

3.2.1 Reference axes

The reference axis system defined for a woven roving is the same as for an unidirectional, with the following denomination:

1 : Axis parallel to warp direction

2 : Axis parallel to weft direction

3 : Axis normal to the plane containing axes 1 and 2, leading to the direct reference axis system.

3.2.2 Woven balance coefficient C_{eq}

The woven balance coefficient C_{eq} is equal to the mass ratio of dry reinforcement in warp direction to the total dry reinforcement of woven fabric.

3.2.3 Elastic coefficients

The elastic coefficients of a woven roving as individual layer are estimated by the following formulae:

- Young modulus in warp direction E_{T1}, in N/mm^2:

$$E_{T1} = \frac{1}{e} \cdot \left(A_{11} - \frac{A_{12}^2}{A_{22}}\right)$$

- Young modulus in weft direction E_{T2}, in N/mm^2:

$$E_{T2} = \frac{1}{e} \cdot \left(A_{22} - \frac{A_{12}^2}{A_{11}}\right)$$

- Out-of-plane Young modulus E_{T3}, in N/mm^2:

$$E_{T3} = E_{UD3}$$

- Shear moduli G_{T12}, G_{T13} and G_{T23}, in N/mm^2:

$$G_{T12} = \frac{1}{e} \cdot A_{33}$$

$$G_{T13} = G_{T23} = 0,9 \cdot G_{T12}$$

- Poisson coefficients:

$$\nu_{T12} = \frac{A_{12}}{A_{22}}$$

$$\nu_{T21} = \nu_{T12} \cdot \frac{E_{T2}}{E_{T1}}$$

$$\nu_{T32} = \nu_{T31} = \frac{\nu_{UD32} + \nu_{UD31}}{2}$$

$$\nu_{T13} = \frac{\nu_{UD23} + \nu_{UD13}}{2}$$

where:

$$A_{11} = e \cdot [C_{eq} \cdot Q_{11} + (1 - C_{eq}) \cdot Q_{22}]$$

$$A_{22} = e \cdot [C_{eq} \cdot Q_{22} + (1 - C_{eq}) \cdot Q_{11}]$$

$$A_{12} = e \cdot Q_{12}$$

$$A_{33} = e \cdot Q_{33}$$

with:

$$Q_{11} = \frac{E_{UD1}}{1 - \nu_{UD12} \cdot \nu_{UD21}}$$

$$Q_{22} = \frac{E_{UD2}}{1 - \nu_{UD12} \cdot \nu_{UD21}}$$

$$Q_{12} = \frac{\nu_{UD21} \cdot E_{UD1}}{1 - \nu_{UD12} \cdot \nu_{UD21}}$$

$$Q_{33} = G_{UD12}$$

Note 1: Parameters with suffix UD are the values defined in [3.1] for an UD having the same raw materials and mix ratios as the woven roving under calculation.

3.3 Chopped strand mat

3.3.1 General

A chopped strand mat is assumed to be an isotropic material.

3.3.2 Elastic coefficients

Isotropic assumption allows to define the elastic coefficients of a chopped strand mat with the following formulae:

- Young moduli, in N/mm²:

$$E_{mat1} = E_{mat2} = \frac{3}{8} \cdot E_{UD1} + \frac{5}{8} \cdot E_{UD2}$$

$$E_{mat3} = E_{UD3}$$

- Shear moduli, in N/mm²:

$$G_{mat12} = \frac{E_{mat1}}{2 \cdot (1 + \nu_{mat21})}$$

$$G_{mat23} = G_{mat31} = 0,7 \cdot G_{UD12}$$

- Poisson coefficients:

$$\nu_{mat12} = \nu_{mat21} = \nu_{mat32} = \nu_{mat13} = 0,3$$

Note 1: Parameters with suffix UD are the values defined in [3.1] for an UD having the same raw materials and mix ratios as the mat under calculation.

3.4 Combined fabric

3.4.1 A combined fabric, as defined in Sec 4, [3.3.6], is to be considered as a series of individual layers such as unidirectionals, woven rovings or chopped strand mats. Each component is analysed as defined in [3.1], [3.2] or [3.3], according to the type of reinforcement fabric.

4 In-plane rigidity and flexibility of an individual layer

4.1 In-plane characteristics

4.1.1 Rigidity

The rigidity R, defined in the individual layer coordinate system, is as follows:

$$[\sigma]_{1,2} = [\bar{R}] \cdot [\varepsilon]_{1,2}$$

equivalent to, under matrix notation:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} \bar{R}_{11} & \bar{R}_{12} & 0 \\ \bar{R}_{21} & \bar{R}_{22} & 0 \\ 0 & 0 & \bar{R}_{33} \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix}$$

where:

[σ] : Matrix of in-plane stresses

[ε] : Matrix of in-plane strains

[R] : Local matrix of rigidity.

Elements of the matrix of rigidity are specific to the types of reinforcement fabrics and are defined in Tab 3.

Table 3 : Elements of matrix of rigidity

	For unidirectionals (UD)	For woven rovings (WR)	For mats (CSM)	Core material
R11	$E_{UD1}/(1-\nu_{UD12} \cdot \nu_{UD21})$	$E_{T1}/(1-\nu_{T12} \cdot \nu_{T21})$	$E_{mat1}/(1-\nu_{mat12}^2)$	$E_1/(1-\nu_{12} \cdot \nu_{21})$
R22	$E_{UD2}/(1-\nu_{UD12} \cdot \nu_{UD21})$	$E_{T2}/(1-\nu_{T12} \cdot \nu_{T21})$	$E_{mat2}/(1-\nu_{mat21}^2)$	$E_2/(1-\nu_{12} \cdot \nu_{21})$
R12	$\nu_{UD21} \cdot E_{UD1}/(1-\nu_{UD12} \cdot \nu_{UD21})$	$\nu_{T21} \cdot E_{T1}/(1-\nu_{T12} \cdot \nu_{T21})$	$\nu_{mat21} \cdot E_{mat1}/(1-\nu_{mat12}^2)$	$\nu_{21} \cdot E_1/(1-\nu_{12} \cdot \nu_{21})$
R21	$\nu_{UD12} \cdot E_{UD2}/(1-\nu_{UD12} \cdot \nu_{UD21})$	$\nu_{T12} \cdot E_{T2}/(1-\nu_{T12} \cdot \nu_{T21})$	$\nu_{mat12} \cdot E_{mat2}/(1-\nu_{mat21}^2)$	$\nu_{12} \cdot E_2/(1-\nu_{12} \cdot \nu_{21})$
R33	G_{UD12}	G_{T12}	G_{mat12}	G_{12}

Table 4 : Elements of matrix of flexibility

	For unidirectionals (UD)	For woven rovings (WR)	For mats (CSM)	Core material
S11	$1/E_{UD1}$	$1/E_{T1}$	$1/E_{mat}$	$1/E_1$
S22	$1/E_{UD2}$	$1/E_{T2}$	$1/E_{mat}$	$1/E_2$
S12	$-\nu_{UD21}/E_{UD2}$	$-\nu_{T21}/E_{T2}$	$-\nu_{mat}/E_{mat}$	$-\nu_{21}/E_2$
S21	$-\nu_{UD12}/E_{UD1}$	$-\nu_{T12}/E_{T1}$	$-\nu_{mat}/E_{mat}$	$-\nu_{12}/E_1$
S33	$1/G_{UD12}$	$1/G_{T12}$	$1/G_{mat12}$	$1/G_{12}$

4.1.2 Flexibility

The flexibility S, defined in the individual layer coordinate system, is as follows:

$$[\varepsilon]_{1,2} = [\bar{S}] \cdot [\sigma]_{1,2}$$

equivalent to, under matrix notation:

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} = \begin{bmatrix} \bar{S}_{11} & \bar{S}_{12} & 0 \\ \bar{S}_{21} & \bar{S}_{22} & 0 \\ 0 & 0 & \bar{S}_{33} \end{bmatrix} \cdot \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix}$$

where:

[σ] : Matrix of in-plane stresses

[ε] : Matrix of in-plane strains

[S] : Local flexibility matrix of the individual layer.

Elements of the matrix of flexibility are specific to the types of reinforcement fabrics and are defined in Tab 4.

5 In-plane theoretical individual layer breaking stresses

5.1 Definitions

5.1.1 Theoretical breaking stress calculations

The in-plane theoretical individual layer breaking stresses are defined, in N/mm², as the maximum breaking stresses of the individual layer in its local coordinate system, taking into account the type and the direction of the stresses. The theoretical breaking stresses are obtained from the following formulae:

$\sigma_{brt1} = \varepsilon_{brt1} \cdot E_1 \cdot Coef_{res}$

$\sigma_{brc1} = \varepsilon_{brc1} \cdot E_1 \cdot Coef_{res}$

$\sigma_{brt2} = \varepsilon_{brt2} \cdot E_2 \cdot Coef_{res}$

$\sigma_{brc2} = \varepsilon_{brc2} \cdot E_2 \cdot Coef_{res}$

$\tau_{br12} = \gamma_{br12} \cdot G_{12} \cdot Coef_{res}$

$\tau_{brIL1} = \gamma_{brIL1} \cdot G_{23} \cdot Coef_{res}$

$\tau_{brIL2} = \gamma_{brIL2} \cdot G_{13} \cdot Coef_{res}$

where:

E_1, E_2, G_{12}, G_{13}, G_{23} : Elastic coefficients defined in [3], in N/mm², for the individual layer considered according to the type of reinforcement (UD, WR, CSM)

$Coef_{res}$: Coefficient defined in Tab 5.

Theoretical breaking strains, in %, given in Tab 6, as applicable for raw materials type, and defined as follow:

ε_{brt1}, ε_{brc1} : Theoretical breaking strains, in %, respectively in tensile and in compression, of an individual layer in direction 1 of its local coordinate system

ε_{brt2}, ε_{brc2} : Theoretical breaking strains, in %, respectively in tensile and in compression, of an individual layer in direction 2 of its local coordinate system

γ_{br12} : Theoretical in-plane breaking shear strain, in %, of an individual layer

γ_{brIL} : Theoretical interlaminar breaking shear strain, in %, of an individual layer

$Coef_{res}$: Coefficient taking into account the adhesive quality of the resin system, as defined in Tab 5.

5.1.2 As a general Rule, mechanical characteristics of an individual layer also depend on the laminating process. In order to simplify calculations of the theoretical breaking stresses defined in [5.1.1], the influence of the laminating process is taken into account by means of a dedicated safety factor (C_F) defined in Sec 2, applied to the whole laminate.

5.1.3 Direct breaking stresses determination approach

Breaking stresses values of individual layers directly deduced from mechanical tests may be considered on a case by case basis instead of theoretical values defined in [5.1.1].

In this case, a program of test is to be submitted to the Society and technical reports, issued in the forms stipulated in standards indicated in App 1, Tab 1, are to be submitted to the Society for examination.

5.1.4 Other raw materials for individual layers

When other raw materials than those defined in Sec 4 are used for individual layers, the different values of breaking stresses listed in [5.1.1] are to be submitted. These values may be obtain by representative mechanical tests.

Table 5 : Coefficient Coefres

Resin systems		
Polyester	Vinylester	Epoxy
0,8	0,9	1,0

Table 6 : Theoretical breaking strains, in %

Reinforcement fabric type		Strains		Reinforcement fibre type					
				E Glass	R Glass	HS Carbon	IM Carbon	HM Carbon	Para-aramid
Reinforcement fabric type	Unidirectionals	Tensile	ε_{brt1}	2,70	3,10	1,20	1,15	0,70	1,70
			ε_{brt2}	0,53	0,44	1,00	0,80	0,50	0,80
		Compression	ε_{brc1}	1,80	1,80	0,85	0,65	0,45	0,35
			ε_{brc2}	1,55	1,10	2,30	2,30	2,10	2,00
		Shear	γ_{br12}	1,80	1,50	1,60	1,70	1,80	2,00
			γ_{br13}, γ_{brIL2}	1,80	1,50	1,60	1,70	1,80	2,00
			γ_{br23}, γ_{brIL1}	2,50	1,80	1,90	1,85	1,80	2,90
	Woven rovings	Tensile	ε_{brt1}	1,80	2,30	1,00	0,80	0,45	1,40
			ε_{brt2}	1,80	2,30	1,00	0,80	0,45	1,40
		Compression	ε_{brc1}	1,80	2,50	0,85	0,80	0,50	0,42
			ε_{brc2}	1,80	2,50	0,85	0,80	0,50	0,42
		Shear	γ_{br12}	1,50	1,50	1,55	1,60	1,85	2,30
			γ_{br13}, γ_{brIL2}	1,80	1,80	1,55	1,60	1,85	2,90
			γ_{br23}, γ_{brIL1}	1,80	1,80	1,55	1,60	1,85	2,90
	Chopped strand mats	Tensile	ε_{brt1}	1,55	NA	NA	NA	NA	NA
			ε_{brt2}	1,55	NA	NA	NA	NA	NA
		Compression	ε_{brc1}	1,55	NA	NA	NA	NA	NA
			ε_{brc2}	1,55	NA	NA	NA	NA	NA
		Shear	γ_{br12}	2,00	NA	NA	NA	NA	NA
			γ_{br13}, γ_{brIL2}	2,15	NA	NA	NA	NA	NA
			γ_{br23}, γ_{brIL1}	2,15	NA	NA	NA	NA	NA
Note 1: NA = Not applicable.									

Section 6 Laminate Characteristics and Panel Analysis

1 Application

1.1 General

1.1.1 General

The scantling check of a laminate is carried out by the calculation of safety factors as defined in Sec 2, [1].

The following parameters are to be taken into account to characterise a laminate:

- two geometric parameters to characterise the individual layers:
  - fibre/resin mix ratio
  - individual layer thickness
- five in-plane elastic coefficients to characterise the laminate:
  - longitudinal Young modulus
  - transverse Young modulus
  - two Poisson coefficients
  - shear modulus.

1.1.2 Definitions

In the present Section, the term 'laminate' is used to define the material made from several individual layers, and the term 'panel' or 'laminate panel' to define a hull, superstructure or bulkhead panel supported by stiffeners.

1.1.3 The purpose of the present Section is to define the:

- theoretical main characteristics of a laminate (see Article [2])
- behaviour of a laminate under bending moments, shear forces and in-plane forces (see Article [3])
- behaviour of a laminate under in-plane buckling (see Article [4])
- panel rule analysis under local external loads (see Article [5])
- panel rule analysis under global loads, when applicable (see Article [6]).

1.1.4 Panel rule analysis under local external loads

Panels submitted to local external loads as defined in [5.1.1] are examined under local bending moments and interlaminar shear forces with a "ply by ply" theoretical analysis.

The local distribution of strains and the values of the stresses in each ply through the laminate depend on the:

- type of the individual layers
- position of the individual layers through the laminate thickness
- orientation of the individual layers in relation to the laminate global axis.

1.1.5 Panel rule analysis under global loads

Panels submitted to global loads as defined in [6.1.1] are mainly examined with:

- buckling analysis, considering the global rigidity of the laminate, and
- ply by ply analysis under in-plane and shear forces.

As a rule, the panel rule analysis under global loads is to be carried out when a global strength analysis according to Sec 2, [3] is required.

1.1.6 Panel rule analysis under local external loads combined with global loads

Panels submitted to local external loads combined with global loads as defined in [7.1.1] are mainly examined with:

- buckling analysis, considering the global rigidity of the laminate, and
- ply by ply analysis considering local bending moments and interlaminar shear forces and global in-plane forces.

As a rule, the panel rule analysis under local external loads and global loads is to be carried out when deemed necessary by the Society.

1.2 Laminate calculation methodology

1.2.1 The methodology to review the minimum rule scantling criteria of a panel is defined in Tab 1.

Table 1 : Laminate calculation methodology

Step	Description	Refer to
1	Calculation of the geometric characteristics, elastic coefficients, rigidity and flexibility, and theoretical breaking stresses of each individual layer in its local orthotropic axes	Sec 5
2	Geometrical description of the laminate to define: • position of all the individual layers • orientation of each layer in relation to the global laminate in-plane axes	[2.1.2] and [2.1.3]
3	Calculation of the laminate global elastic coefficients and mechanical characteristics in panel axes, and calculation of critical buckling stress, when applicable	[2.2]
4	Calculation of the loads applied to the panel (local external loads and global loads for buckling, when applicable)	Sec 2
5	Calculation of the laminate median plane deformations	[3.2.1]
6	Calculation of strains and stresses, for each individual layer, in the panel global axes	[3.2.2]
7	Calculation of strains and stresses, for each individual layer, in its own local axes	[3.2.3]
8	Check of the scantling criteria for local scantling, global scantling when applicable and global combined to local scantling when deemed necessary by the Society	Articles [5], [6] and [7]

2 Laminate basic characteristics

2.1 General

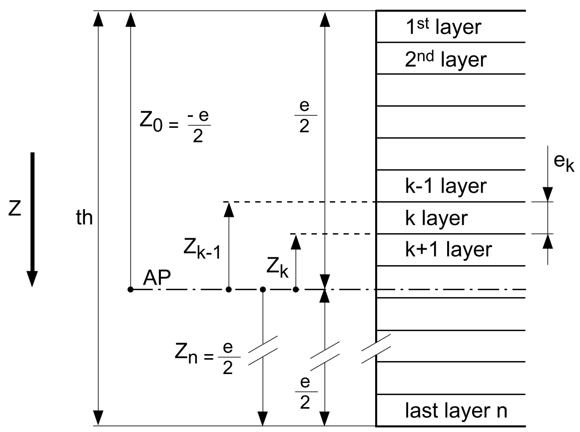
2.1.1 The basic characteristics considered depend on the:

- characteristics of each individual layer, as defined in Sec 5
- position of each individual layer through the laminate thickness, as shown in [2.1.2]
- orientation of each individual layer in relation to the laminate global axes, as defined in [2.1.3].

2.1.2 Position of individual layers

Position of each individual layer through the laminate thickness is referenced as shown on Fig 1.

Figure 1 : Position of individual layers



AP : Median plane of the laminate, located at mid-thickness of the laminate

th : Laminate thickness, in mm

e_k : Thickness of individual layer k, in mm

Z_k : Distance between AP and interface of layers k and k+1:

$$Z_k = \frac{-e}{2} + \sum_{1}^{k} e_i$$

Z_{k-1} : Distance between AP and interface of layers k and k–1:

$$Z_{k-1} = \frac{-e}{2} + \sum_{1}^{k-1} e_i$$

2.1.3 Orientation of individual layers

Orientation between each individual layer local axes and laminate global axes is defined in Fig 2.

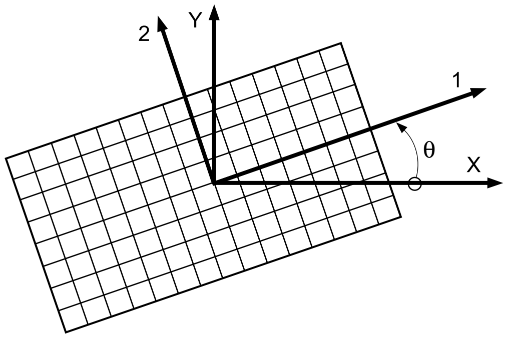
As a general rule, laminate global reference axes are taken similar to the ship reference axes, with:

X : Ship longitudinal axis

Y : Axis perpendicular to the ship longitudinal axis in the laminate plane.

Note 1: Angle θ is considered positive from the global axes to the local axes, as shown on Fig 2.

Figure 2 : Orientation of individual layers in relation to the laminate global axes



2.1.4 Conversion of individual layer characteristics

The matrix of rigidity $[R]_k$ and the matrix of flexibility $[S]_k$ of an individual layer k in the laminate global axes are obtained as follows:

$$[R]_k = \begin{bmatrix} R_{XX} & R_{XY} & R_{XZ} \\ R_{YX} & R_{YY} & R_{YZ} \\ R_{ZX} & R_{ZY} & R_{ZZ} \end{bmatrix}_k = T[\bar{R}]_k T'^{-1}$$

$$[S]_k = \begin{bmatrix} S_{XX} & S_{XY} & S_{XZ} \\ S_{YX} & S_{YY} & S_{YZ} \\ S_{ZX} & S_{ZY} & S_{ZZ} \end{bmatrix}_k = T'[\bar{S}]_k T^{-1}$$

where:

$[R]_k$, $[S]_k$: Rigidity and flexibility matrixes, respectively, of an individual layer k in its local axes, as defined in Sec 5, [4.1.1] and Sec 5, [4.1.2]

T and T′ : Transfer matrixes equal to:

$$T = \begin{bmatrix} (\cos\theta)^2 & (\sin\theta)^2 & -2\cos\theta\sin\theta \\ (\sin\theta)^2 & (\cos\theta)^2 & 2\cos\theta\sin\theta \\ (\cos\theta\sin\theta) & (-\cos\theta\sin\theta) & ((\cos\theta)^2 - (\sin\theta)^2) \end{bmatrix}$$

$$T' = \begin{bmatrix} (\cos\theta)^2 & (\sin\theta)^2 & -\cos\theta\sin\theta \\ (\sin\theta)^2 & (\cos\theta)^2 & \cos\theta\sin\theta \\ (2\cos\theta\sin\theta) & (-2\cos\theta\sin\theta) & ((\cos\theta)^2 - (\sin\theta)^2) \end{bmatrix}$$

where:

T^{-1}, T'^{-1} : Inverse of transfer matrixes T and T′, respectively.

2.1.5 Laminate weight

The total weight per square metre of a laminate, in kg/m², is equal to:

$$W = \left(\sum_1^n \frac{P_{fi}}{M_{fi}}\right) 10^{-3} + \sum P_i$$

where:

P_{fi} : Mass per square metre, in g/m², of dry reinforcement fabric of each individual layer, as defined in Sec 5

M_{fi} : Content in mass of fibre for each individual layer, in %, defined in Sec 5, [2.1.1]

P_i : Weight of foam and adhesive per square metre, in kg/m², for sandwich laminate.

2.2 Elastic coefficients of laminates

2.2.1 Moduli and poisson ratio

The main tensile moduli E_X and E_Y of a laminate, in N/mm², in its two main directions X and Y, are obtained from the following formulae:

- in X direction:

$$E_X = \frac{1}{A'_{11} \cdot th}$$

- in Y direction:

$$E_Y = \frac{1}{A'_{22} \cdot th}$$

The in-plane shear modulus G_{XY}, in N/mm², of a laminate is obtained from the following formula:

$$G_{XY} = \frac{1}{A'_{33} \cdot th}$$

The main poisson ratio ν_X and ν_Y of a laminate in its two main directions X and Y, are obtained from the following formulae:

- in X direction:

$$\nu_X = \frac{A_{21}}{A_{22}}$$

- in Y direction:

$$\nu_Y = \frac{A_{12}}{A_{11}}$$

where:

A'_{11} , A'_{22} , A'_{33} : Terms of the reverse matrix A defined in [2.3.2]

A_{11} , A_{22} , A_{12} ,A_{21}: Terms of the matrix A defined in [2.3.1]

th : Thickness, in mm, of the laminate.

2.2.2 Laminate neutral axis position

The distances V_X and V_Y , in mm, between the global neutral axis of a laminate and the edge of its first individual layer, are defined, in its two main directions X and Y, by the following formulae:

- In X direction:

$$V_X = \frac{\sum E_{Xi} \cdot e_i \cdot Z_i}{\sum E_{Xi} \cdot e_i}$$

- In Y direction:

$$V_Y = \frac{\sum E_{Yi} \cdot e_i \cdot Z_i}{\sum E_{Yi} \cdot e_i}$$

where:

E_{Xi} : Modulus of each individual layer in direction X of the laminate, in N/mm², as defined in [2.2.1]

E_{Yi} : Modulus of each individual layer in direction Y of the laminate, in N/mm², as defined in [2.2.1]

e_i : Thickness of each individual layer, in mm, as defined in Sec 5, [2.2.1]

Z_i : Distance, in mm, between the edge of the laminate and the mid-thickness of each layer, as defined in [2.1.2].

2.2.3 Laminate bending rigidity

The global bending rigidity, in N·mm²/mm, of a laminate may be expressed, in its two main directions X and Y, from the following formulae:

- in X direction:

$$[EI]_x = \frac{1}{D'_{11}}$$

- in Y direction:

$$[EI]_y = \frac{1}{D'_{22}}$$

where:

D'_{11} , D'_{22} : Terms of the reverse matrix D defined in [2.3.1].

2.3 Matrix notation

2.3.1 Global rigidity matrix

The global rigidity matrix is defined as follows:

$$\begin{bmatrix} A & B \\ B & D \end{bmatrix} = \begin{bmatrix} A_{ij} & B_{ij} \\ B_{ij} & D_{ij} \end{bmatrix}$$

with:

A_{ij} : Tensile rigidity (matrix [3x3])

$$A_{ij} = \sum_{1}^{n} (R_{ij})_K \cdot e_k$$

B_{ij} : Tensile and bending coupling effect (matrix [3x3])

$$B_{ij} = \frac{1}{2} \cdot \sum_{1}^{n} (R_{ij})_K \cdot (Z_k^2 - Z_{k-1}^2)$$

D_{ij} : Bending rigidity (matrix [3x3])

$$D_{ij} = \frac{1}{3} \cdot \sum_{1}^{n} (R_{ij})_K \cdot (Z_k^3 - Z_{k-1}^3)$$

2.3.2 Reverse global rigidity matrix

The reverse global rigidity matrix is defined as follows:

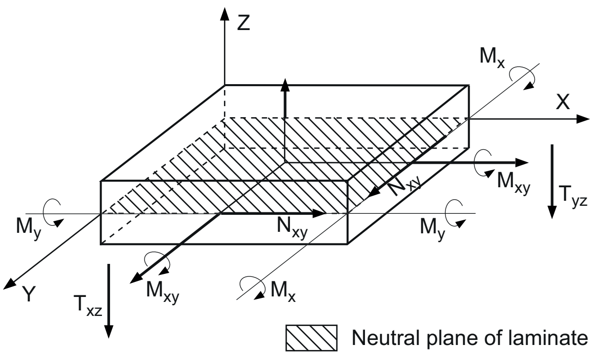
$$\begin{bmatrix} A & B \\ B & D \end{bmatrix}^{-1} = \begin{bmatrix} A' & B' \\ B' & D' \end{bmatrix}$$

3 Laminate behaviour under bending moments, shear forces and in-plane forces

3.1 General

3.1.1 The present Article defines the behaviour of a laminate and the distribution in each individual layer of strains and stresses under bending moments M_i, shear forces T_i and in-plane forces N_i, as shown on Fig 3.

Figure 3 : Application of forces and moments



3.1.2 Bending moments M_i and shear forces T_i

Bending moments M_x and M_y result from local loads applied perpendicular to the laminate plane, as defined in Sec 2, [2.2].

Bending moment M_{xy} results from a torsional moment around axes parallel to the laminate plane. As a general rule, this moment is equal to zero

Shear forces T_{xz} and T_{yz} result from local loads applied perpendicular to the laminate plane, as defined in Sec 2, [2.2].

3.1.3 In-plane forces N_i

In-plane tensile or compression forces, N_x and N_y, and in-plane shear force N_{xy} result from global hull girder longitudinal loads or from global transverse loads for catamaran, as defined in Sec 2, [3].

When laminate scantling is checked under local external pressure only, N_x, N_y and N_{xy} are to be taken equal to 0

3.2 Laminate behaviour under bending moments M_i and in-plane forces N_i

3.2.1 Deformations of laminate median plane

Strains and curved deformations of the laminate median plane are obtained from the following formula:

$$\begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ K_x \\ K_y \\ K_{xy} \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix}^{-1} \cdot \begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \cdot 10^{-3} \\ M_y \cdot 10^{-3} \\ M_{xy} \cdot 10^{-3} \end{bmatrix}$$

where:

ε^0_x : Tensile or compression strain of the laminate median plane in X direction

ε^0_y : Tensile or compression strain of the laminate median plane in Y direction

γ^0_{xy} : Shear strain of the laminate median plane in XY plane

K_x : Curved deformation of the laminate median plane around Y axis

K_y : Curved deformation of the laminate median plane around X axis

K_{xy} : Twist deformation of the laminate median plane around X and Y axes

$[ABD]^{-1}$: Reverse global rigidity matrix, as defined in [2.3].

3.2.2 Strains of individual layers in the laminate global axes

The in-plane strains ε_x , ε_y and γ_{xy} of each individual layer, calculated at its mid-thickness in the laminate global axes, are given by the following formula:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}_k = \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} + \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix} \cdot \frac{Z_k + Z_{k-1}}{2}$$

Note 1: As a general rule, for core materials, the values of ε_x and ε_y are to be calculated at each interface between the core and the laminate skins.

3.2.3 Strains and stresses of individual layers in their own local axes

The in-plane strains ε_1, ε_2 and γ_{12} of each individual layer, calculated at its mid-thickness in its own local axes, are given by the following formula:

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix}_k = T'^{-1} \cdot \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}_k$$

where:

T' : Transfer matrix defined in [2.1.4] for each individual layer.

The local stresses σ_1, σ_2 and τ_{12} in an individual layer expressed in its own local axes, at mid-thickness, are defined by the following formula:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix}_k = [\overline{R}] \cdot \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix}_k$$

where:

[R] : Rigidity matrix defined in Sec 5, [4] for each individual layer.

Note 1: For core material of sandwich laminates, the local stresses are expressed, in its own local axes, at top and bottom of the core thickness.

3.3 Laminate behaviour under out plane shear forces T_i

3.3.1 Interlaminar shear stress in laminate global axes

The interlaminar shear stresses τ_{xz} and τ_{yz} between two layers k and k–1, in the global X and Y directions of the laminate induced by shear loads, are determined by the following formula:

$$\begin{bmatrix} \tau_{yz} \\ \tau_{xz} \end{bmatrix}_k = \begin{bmatrix} H_{44} & H_{45} \\ H_{54} & H_{55} \end{bmatrix}_k \cdot \begin{bmatrix} T_{yz} \\ T_{xz} \end{bmatrix}$$

where:

T_{xz}, T_{yz} : Shear loads normal to the median plane of the laminate as shown on Fig 3

$[H_{44}]_k$, $[H_{45}]_k$, $[H_{54}]_k$, $[H_{55}]_k$: Shear constants of layer k, equal to:

$$H_{44} = [C_{yz}]_{k,5} - [R_{21}\ R_{22}\ R_{23}]_k \cdot \begin{bmatrix} Z_{k-1} \cdot B'_{12} + \frac{Z_{k-1}^2}{2} \cdot D'_{12} \\ Z_{k-1} \cdot B'_{22} + \frac{Z_{k-1}^2}{2} \cdot D'_{22} \\ Z_{k-1} \cdot B'_{32} + \frac{Z_{k-1}^2}{2} \cdot D'_{32} \end{bmatrix}$$

$$H_{45} = [C_{yz}]_{k,6} - [R_{21}\ R_{22}\ R_{23}]_k \cdot \begin{bmatrix} Z_{k-1} \cdot B'_{13} + \frac{Z_{k-1}^2}{2} \cdot D'_{13} \\ Z_{k-1} \cdot B'_{23} + \frac{Z_{k-1}^2}{2} \cdot D'_{23} \\ Z_{k-1} \cdot B'_{33} + \frac{Z_{k-1}^2}{2} \cdot D'_{33} \end{bmatrix}$$

$$H_{54} = [C_{xz}]_{k,6} - [R_{11}\ R_{12}\ R_{13}]_k \cdot \begin{bmatrix} Z_{k-1} \cdot B'_{13} + \frac{Z_{k-1}^2}{2} \cdot D'_{13} \\ Z_{k-1} \cdot B'_{23} + \frac{Z_{k-1}^2}{2} \cdot D'_{23} \\ Z_{k-1} \cdot B'_{33} + \frac{Z_{k-1}^2}{2} \cdot D'_{33} \end{bmatrix}$$

$$H_{55} = [C_{xz}]_{k,4} - [R_{11}\ R_{12}\ R_{13}]_k \cdot \begin{bmatrix} Z_{k-1} \cdot B'_{11} + \frac{Z_{k-1}^2}{2} \cdot D'_{11} \\ Z_{k-1} \cdot B'_{21} + \frac{Z_{k-1}^2}{2} \cdot D'_{21} \\ Z_{k-1} \cdot B'_{31} + \frac{Z_{k-1}^2}{2} \cdot D'_{31} \end{bmatrix}$$

with:

$[R_{ij}]_k$: Terms of the matrix of rigidity of the layer k defined in Sec 5, [4.1.1]

B'_{ij}, D'_{ij} : Terms of the reverse global matrix defined in [2.3.2]

$[C_{yz}]_{k,5}$, $[C_{yz}]_{k,6}$: Fifth and sixth terms of the matrix $[C_{yz}]_k$ defined hereafter

$[C_{xz}]_{k,4}$, $[C_{xz}]_{k,6}$: Fourth and sixth terms of the matrix $[C_{xz}]_k$ defined hereafter

$[C_{yz}]_k$, $[C_{xz}]_k$: Shear distribution coefficients for individual layer k (matrix 1x6) equal to:

$$[C_{yz}]_k = [C_{yz}]_{k-1} + \left\{ [R_2]_k - [R_2]_{k-1} \right\} \cdot [M]_k$$

$$[C_{xz}]_k = [C_{xz}]_{k-1} + \left\{ [R_1]_k - [R_1]_{k-1} \right\} \cdot [M]_k$$

with:

$[C_{xz}]_{k-1}$, $[C_{yz}]_{k-1}$: Shear distribution coefficients (matrix [1x6]) for layer k–1

$[R_1]_k$, $[R_1]_{k-1}$: First line of matrix of rigidity [R] (defined in [2.1.3]) for layers k and k–1

$[R_2]_k$, $[R_2]_{k-1}$: Second line of matrix of rigidity [R] (defined in [2.1.3]) for layers k and k–1

Note 1: For the first layer (k = 1), the following coefficients are to be taken equal to zero.

$[C_{yz}]_{k-1} = [C_{xz}]_{k-1} = [R_2]_{k-1} = [R_1]_{k-1} = 0$

with:

$[M]_k$: Matrix 3x6 defined as follow:

$$[M]_k = [\,[M_{AB}]_k\,[M_{BD}]_k\,]$$

where:

$[M_{AB}]_k$: Matrix 3x3 equal to:

$$[M_{AB}]_k = \left[Z_{k-1} \cdot A' + \frac{Z_{k-1}^2}{2} \cdot B' \right]$$

$[M_{BD}]_k$: Matrix 3x3 equal to:

$$[M_{BD}]_k = \left[Z_{k-1} \cdot B' + \frac{Z_{k-1}^2}{2} \cdot D'\right]$$

A′, B′, D′ : Terms of the reverse global rigidity matrix [ABD] as defined in [2.3].

3.3.2 Interlaminar shear stress in individual layer local axes

The interlaminar shear stresses between two layers k and k–1, in the local orthotropic axes of the individual layers, are obtained from the following formula:

$$\begin{bmatrix}\tau_{23}\\ \tau_{13}\end{bmatrix}_k = \begin{bmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{bmatrix} \cdot \begin{bmatrix}\tau_{yz}\\ \tau_{xz}\end{bmatrix}_k$$

τ_{23} and τ_{13} are also named, respectively, τ_{IL1} and τ_{IL2} in the present Rule Note.

4 Laminate behaviour under in-plane buckling

4.1 General

4.1.1 The present Article defines the critical buckling stresses of a laminate subjected to in-plane compression force N_X, or N_Y or in-plane shear force N_{XY} as shown on Fig 5.

4.1.2 Boundary conditions

As a general rule, the boundary conditions are considered as follows:

- for monolithic laminates, all the laminate edges are supposed simply supported in way of the laminate supports
- for sandwich laminates, all the laminate edges are supposed clamped in way of the laminate supports.

Note 1: For sandwich laminate, global buckling only is taken into account. As a general rules, the specific skin buckling modes, such as shear crimping, local face dimpling and face wrinkling, are not sampling cases with usual sandwich used in ship hull construction.

When particular sandwich designs are used, such as foam core with low density, honeycomb core or thin face skins, these specific buckling modes are specially examined on a case-by-case basis.

4.1.3 Material characteristics

Hypotheses on the main material characteristics, for buckling behaviour of the laminates, are as follows:

- monolithic laminates and sandwich face skins of sandwich are considered as orthotropic material
- core material of sandwich is considered as isotropic material.

4.2 Buckling of monolithic laminate

4.2.1 General

The critical compression buckling stresses in the two main global axis X and Y of a monolithic laminate are to be calculated taking into account the following parameters:

a, b : Sides of the laminate, in m, as shown in Fig 5

α : Aspect ratio, equal to: $\alpha = a / b$

t : Laminate thickness, in mm

D_{ij} : As defined in [2.3], in N·mm²/mm, according to the global axes X and Y as shown on Fig 5.

4.2.2 Critical buckling stress in X-direction and Y-direction

The critical compression buckling stress σ_C, in N/mm², in X-direction and Y-direction of a monolithic laminate with relation to its main dimensions a and b as shown on Fig 5, is estimated from the following formulae:

- Critical buckling under X-direction:

$$\sigma_C = \frac{\pi^2 \cdot 10^{-6}}{m^2 \cdot a^2 \cdot t} \cdot D_X$$

where:

$$D_X = D_{11} \cdot m^4 + 2(D_{12} + 2D_{33}) \cdot m^2 \cdot \alpha^2 + D_{22} \cdot \alpha^4$$

m : Number of buckling half-waves in X-direction, depending on the parameter α, as follows:

if $\alpha \le \sqrt{2}\left(\frac{D_{11}}{D_{22}}\right)^{1/4}$: m = 1

if $\sqrt{2}\left(\frac{D_{11}}{D_{22}}\right)^{1/4} < \alpha \le \sqrt{6}\left(\frac{D_{11}}{D_{22}}\right)^{1/4}$: m = 2

if $\alpha > \sqrt{6}\left(\frac{D_{11}}{D_{22}}\right)^{1/4}$: m = 3

- Critical buckling under Y-direction:

$$\sigma_C = \frac{\pi^2 \cdot 10^{-6}}{n^2 \cdot b^2 \cdot t} \cdot D_Y$$

where:

$$D_Y = \frac{D_{11}}{\alpha^4} + \frac{2(D_{12} + 2D_{33})}{\alpha^2} \cdot n^2 + D_{22} \cdot n^4$$

n : Number of buckling half-waves in loading Y-direction. It depends on α, as follows:

$$\text{if } \frac{1}{\alpha} \le \sqrt{2}\left(\frac{D_{22}}{D_{11}}\right)^{1/4} \quad : n = 1$$

$$\text{if } \sqrt{2}\left(\frac{D_{22}}{D_{11}}\right)^{\frac{1}{4}} < \frac{1}{\alpha} \le \sqrt{6}\left(\frac{D_{22}}{D_{11}}\right)^{1/4} \quad : n = 2$$

$$\text{if } \frac{1}{\alpha} > \sqrt{6}\left(\frac{D_{22}}{D_{11}}\right)^{1/4} \quad : n = 3$$

4.2.3 Critical buckling under shear

The critical shear buckling stress τ_C, in N/mm², is estimated with the following formula:

$$\tau_C = C_\beta \cdot \frac{(D_{11} \cdot D_{22}^3)^{1/4}}{t \cdot \left(\frac{c_1}{2}\right)^2} \cdot 10^{-6}$$

where:

t : Laminate thickness, in mm

C_β : Coefficient depending on β and θ:

$C_\beta = (7{,}1\theta + 3{,}9)\,\beta^2 + (7{,}3\theta^3 - 11{,}7\theta^2 + 3{,}2\theta - 0{,}8)\,\beta + 5{,}2\theta + 8{,}1$

with:

$$\theta = \frac{D_{12} + 2D_{33}}{\sqrt{D_{11} D_{22}}}$$

$$\beta = \frac{c_1}{c_2}\left(\frac{D_{11}}{D_{22}}\right)^{1/4}$$

c_1 : Greater side a or b of the laminate panel, in m

c_2 : Smaller value of side a or b of the laminate panel, in m.

4.3 Buckling of sandwich laminate

4.3.1 General

The critical compression buckling stresses in the two main global axis X and Y of a sandwich laminate are to be calculated taking into account the following parameters:

a, b : Sides of the laminate, in m, as shown in Fig 5

t_{F1} : Upper face skin thickness, in mm

t_{F2} : Lower face skin thickness, in mm

t_C : Core thickness, in mm

$E_{tX,1}$, $E_{tX,2}$: Tensile moduli in X-direction, in N/mm², of upper or lower face skin respectively, calculated according to [2.2.1]

$E_{tY,1}$, $E_{tY,2}$: Tensile moduli in Y-direction, in N/mm², of upper or lower face skin respectively, calculated according to [2.2.1]

E_C : Tensile modulus, in N/mm² of the core

$G_{XY,1}$, $G_{XY,2}$: In-plane shear modulus of, respectively, the upper and the lower face skins of sandwich panel in laminate plane XY, calculated according to [2.2.1]

G_C : In-plane shear modulus, in N/mm² of the core

D_{ij} : As defined in [2.3], in N·mm²/mm, according to the global axes X and Y as shown on Fig 5

[EI] : Global flexural rigidity of the sandwich panel to be obtained, in N·mm²/mm, from the following formula:

$$[EI] = \sqrt{D_{11} \cdot D_{22}}$$

4.3.2 Critical buckling stress in X-direction and Y-direction

a) Critical buckling stress calculation:

The critical compression buckling stress $\sigma_{C\text{ , in N/mm}^2}$, in X-direction and Y-direction of a sandwich laminate with relation to its main dimensions a and b as shown on Fig 5, is estimated from the following formulae:

- Critical buckling under X-direction:

$$\sigma_c = E_{tX} \cdot \frac{\pi^2 \cdot [EI]}{b^2 \cdot H_X} \cdot K_X \cdot 10^{-6}$$

where:

$$[EI] = \sqrt{D_{11} \cdot D_{22}}$$

E_{tX} : Min ($E_{tX,1}$,$E_{tX,2}$)

H_X : Global compression rigidity in X-direction, to be calculated, in N/mm, as follows:

$$H_X = E_{tX,\,1} \cdot t_{F1} + E_{tX,\,2} \cdot t_{F2} + E_C \cdot t_C$$

Note 1: In case of anisotropic core, E_C is to be taken equal to the core tensile modulus in the X direction of the laminate.

K_X : Buckling coefficient K in X-direction calculated according to b)

- Critical buckling under Y-direction:

$$\sigma_c = E_{tY} \cdot \frac{\pi^2 \cdot [EI]}{a^2 \cdot H_Y} \cdot K_Y \cdot 10^{-6}$$

where:

E_{tY} : Min ($E_{tY,1}$,$E_{tY,2}$)

H_Y : Global compression rigidity in Y-direction, to be calculated, in N/mm, as follows:

$$H_Y = E_{tY,\,1} \cdot t_{F1} + E_{tY,\,2} \cdot t_{F2} + E_C \cdot t_C$$

Note 2: In case of anisotropic core, E_C is to be taken equal to the core tensile modulus in the Y direction of the laminate

K_Y : Buckling coefficient K in Y-direction calculated according to b)

b) Buckling coefficient K:

The buckling coefficients K_X and K_Y are to be taken equal to the value of K obtained from the following formulae, taking into account in these formulae a value of α equal to:

- α = a/b for K_X
- α = b/a for K_Y

The buckling coefficient K is to be calculated in relation with the boundary conditions as follow:

- simply supported conditions (given for information only):
  - if $\alpha \geq 0,9 \cdot \frac{1}{V^{0,\,15}} - 0,45$, or if $\alpha \geq 0,9$:

    $K = 2\ V^2 - 4{,}1\ V + 3{,}1$

  - if $\alpha < 0,9 \cdot \frac{1}{V^{0,\,15}} - 0,45$:

    $K = A\ \alpha^2 + B\ \alpha + C$

- clamped conditions:
  - if $\alpha \geq 1{,}4$:

    $K = A\ \alpha^B$

  - if $\alpha < 1{,}4$

    $K = A\ \alpha^2 + B\ \alpha + C$

where V is calculated as follow:

- For the calculation of K_X in X-direction:

$$V = \frac{\pi^2 \cdot [EI]}{b^2 \cdot G_C \cdot t_C} \cdot 10^{-6} \leq 0{,}4$$

- For the calculation of K_Y in Y-direction:

$$V = \frac{\pi^2 \cdot [EI]}{a^2 \cdot G_C \cdot t_C} \cdot 10^{-6} \leq 0{,}4$$

A, B, C : As defined in Tab 2.

Table 2 : Values of A, B and C

Conditions		Coefficients
Simply supported	$V \le 0,2$	$A = 120\ V^2 - 116\ V + 20,4$
		$B = -\ 350\ V^2 + 227\ V - 36,8$
		$C = 205\ V^2 - 113,5\ V + 19,7$
	$V > 0,2$	$A = -\ 2\ V + 2$
		$B = -\ 10,8\ V^2 + 19,3\ V - 8,5$
		$C = 5\ V^2 - 10\ V + 6$
Clamped	$\alpha < 1,4$	$A = (74V^2 - 45,7V + 6,4) \ge 0$
		$B = (428,7V^3 - 451,5V^2 + 158,8V - 18,7) \le 0$
		$C = (-540,6V^3 + 501,3V^2 - 164V + 22,5) \ge 2,4$
	$\alpha \ge 1,4$	$A = (-164,1V^3 + 149,7V^2 - 51,6V + 9,6) \ge 2,4$
		$B = (-2,6V^2 + 1,7V - 0,28) \le 0$

4.3.3 Critical buckling under shear

The critical shear buckling stress τ_C, in N/mm², is estimated from the following formula:

$$\tau_C = \frac{\pi^2 \cdot G_{XY} \cdot [EI]}{c_1^{\ 2} \cdot N} \cdot K_2 \cdot 10^{-6}$$

where:

G_{XY} : Min ($G_{XY,\,1}$; $G_{XY,\,2}$)

N : Global shear rigidity to be calculated as follows:

$$N = G_{XY,1} \cdot t_{F1} + G_{XY,2} \cdot t_{F2} + G_C \cdot t_C$$

c_1 : Smaller side a or b of the laminate panel, in m

K_2 : Buckling coefficient, obtained from the following formulae:

- simply supported conditions (given for information only):
  - if $0 \le V \le \dfrac{1}{1 + c^2}$:

    $$K_2 = \frac{4}{3} \cdot \frac{4 + 3c^2}{1 + \frac{1}{3} \cdot (13 + 9c^2) \cdot V}$$

  - if $V > \dfrac{1}{1 + c^2}$:

    $$K_2 = \frac{1}{V}$$

- clamped conditions:
  - if $0 \le V \le \dfrac{3}{4(1 + c^2)}$:

    $$K_2 = \frac{1}{3} \cdot \frac{27 + 17c^2}{1 + \frac{1}{3} \cdot (23 + 13c^2) \cdot V}$$

  - if $V > \dfrac{3}{4(1 + c^2)}$:

    $$K_2 = \frac{1}{V}$$

with:

V : Greater value of V as defined in [4.3.2] b)

$c^2 = c_1^{\ 2} / c_2^{\ 2}$

c_2 : Greater value of side a or b of the laminate panel, in m.

5 Rules analysis of panel under local loads

5.1 General

5.1.1 Application and local loads

All panel sustaining lateral pressures are to be checked according to the present Article.

As a general rule, the bending moments and shear forces induced by lateral pressures are to be calculated according to [5.2] to [5.6] for the following local lateral loads:

- sea pressures
- bottom slamming loads when applicable
- impact pressure on side shell
- internal pressures
- wheeled loads
- ice loads on side shell.

The local loads are defined in Sec 2, [2.2].

5.1.2 Analysis and scantling criteria

The panel analysis is carried out by a "ply by ply" analysis of the laminate.The stresses in each layer of the laminate are calculated as defined in [3], taking into account the bending moments M_i and the shear forces T_i induced by the local loads defined in [5.1.1].

The main scantling criteria to be checked are:

a) Maximum stress in each layer:

The main stresses in each layer of the panel laminate are to be in compliance with the following criteria:

$\sigma \leq \sigma_{br} / SF$

$\tau \leq \tau_{br} / SF$

where:

σ, τ : Actual stresses in each layer as defined in [3.2.3] and [3.3.2] respectively

σ_{br}, τ_{br} : Theoretical breaking stresses of layers as defined in Sec 5

SF : Safety factor as defined in Sec 2, [1.3].

b) Combined stress in each layer:

The combined criterion SF_{CS} is to be in compliance with the equation defined in Sec 2, [1.3.3].

5.1.3 Bending moments and shear forces distributions

The main axes X and Y, the dimensions a and b and the bending rigidities D_{11} and D_{22} of the panel are to be considered as shown on Fig 5:

- a and D_{11}: along X axis of the panel
- b and D_{22}: along Y axis of the panel.

The bending moments to be considered, induced by local loads, are (see Fig 5):

- main bending moment M_x around Y axis, calculated at the middle of the panel boundary b
- main bending moment M_y around X axis, calculated at the middle of the panel boundary a
- secondary bending moment M'_x around Y axis, calculated at the middle of the panel boundary a
- secondary bending moment M'_y around X axis, calculated at the middle of the panel boundary b.

Shear forces T_{xz} and T_{yz} induced by the lateral pressure, as shown on Fig 5, are the shear forces on side "a" and on side "b", respectively.

The values of bending moments and shear forces are to be combined at the middle of each sides a and b of the panel boundary, as follows:

- side "a": taking simultaneously into account M_y, M'_x and T_{xz}
- side "b": taking simultaneously into account M_x, M'_y and T_{yz}.

The sign of the moments is to be chosen in order to respect the tensile and compression faces of the laminate under lateral pressure, as shown on Fig 5.

Each side of the laminate panel is considered as clamped for the rule analysis under local loads.

5.1.4 Equivalent dimensions of the panel

The following parameters are to be taken into account for the calculation of the bending moments and shear forces induced by local lateral loads:

a) Equivalent dimension of the panel:

The equivalent length, in m, of the laminate panel in X and Y directions are respectively:

$$a_0 = a \cdot \sqrt[4]{D/D_{11}}$$

$$b_0 = b \cdot \sqrt[4]{D/D_{22}}$$

where:

- a : Side of the panel in X direction, in m, as shown in Fig 5
- b : Side of the panel in Y direction, in m, as shown in Fig 5
- D_{ij} : As defined in [2.3], in N·mm²/mm
- D : Equivalent bending rigidity, in N·mm²/mm, equal to:

$$D = \sqrt{D_{11} \cdot D_{22}}$$

b) Reduction factors for wide base of stiffeners:

Where the panel is supported by a stiffener of omega type, a reduction factor may be applied for the calculation of the bending moments defined as follow:

$$k_{S,X} = 1 - 3 \cdot \left(\frac{w_{S,X}}{a}\right) \cdot \left(1 - \frac{w_{S,X}}{a}\right) > 0,4$$

$$k_{S,Y} = 1 - 3 \cdot \left(\frac{w_{S,Y}}{b}\right) \cdot \left(1 - \frac{w_{S,Y}}{b}\right) > 0,4$$

with a, b, $w_{S,X}$ and $w_{S,Y}$, in m, as shown in Fig 4 and Fig 5.

Figure 4 : Definition of $w_{S,X}$ and $w_{S,Y}$

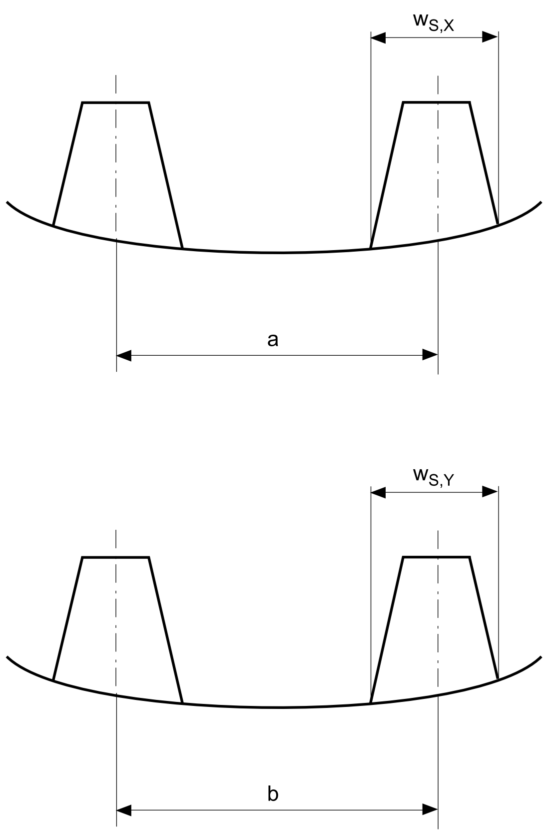
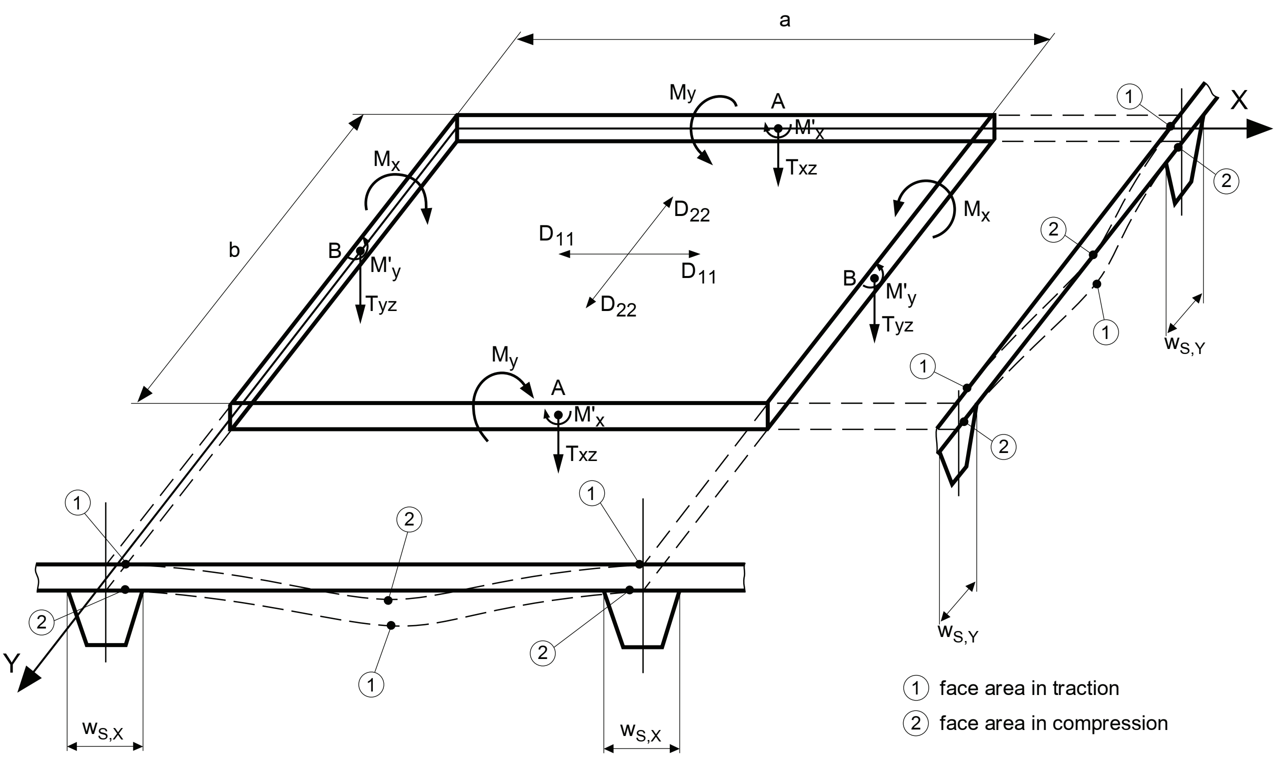


Figure 5 : Bending moments and shear forces



5.2 Bending moments and transverse shear forces calculation for panel under sea or internal pressures

5.2.1 Bending moments

The bending moments induced by sea pressure or internal pressures are to be obtained, per metre width of laminate, in kN·m/m, from the Tab 3.

5.2.2 Transverse shear forces

The transverse shear forces T_{xz} and T_{yz} induced by sea pressures or internal pressures are to be obtained, per metre width of laminate, in kN/m from Tab 4.

Table 3 : Bending moments under sea or internal pressures

Bending moment and α_0	$a_0 \geq b_0$	$a_0 < b_0$
M_x	$F_2 \cdot p_S \cdot b_0^2 \cdot k_{S,X}$	$F_1 \cdot p_S \cdot a_0^2 \cdot k_{S,X}$
M_y	$F_1 \cdot p_S \cdot b_0^2 \cdot k_{S,Y}$	$F_2 \cdot p_S \cdot a_0^2 \cdot k_{S,Y}$
M'_x	$\nu_y . E_x . M_y / E_y$	
M'_y	$\nu_x . E_y . M_x / E_x$	
α_0	$(a_0 / b_0) \leq 2$	$(b_0 / a_0) \leq 2$

Note 1:
F_1, F_2 : Coefficients equal to:
$F_1 = 0{,}0343\ \alpha_0^2 - 0{,}1333\ \alpha_0 + 0{,}0471$
$F_2 = 0{,}0113\ \alpha_0^2 - 0{,}0382\ \alpha_0 - 0{,}0251$
a_0, b_0 : Equivalent dimensions of the panel as defined in [5.1.4]a), in m
$k_{s,x}$, $k_{s,y}$: Reduction factor for wide base of stiffeners as defined in [5.1.4], b)
E_x, E_y, ν_x, ν_y: Moduli and poisson ratio as defined in [2.2.1]
p_S : Local pressure, in kN/m² as defined in Sec 2, [2.2]

Table 4 : Shear forces under sea or internal pressures

Shear force and α_0	$(a_0-w_{s,x}) \geq (b_0-w_{s,y})$	$(a_0-w_{s,x}) \leq (b_0-w_{s,y})$
T_{yz}	$F'_1 . (b_0-w_{s,y}) . p_s$	$F'_2 . (a_0-w_{s,x}) . p_s$
T_{xz}	$F'_2 . (b_0-w_{s,y}) . p_s$	$F'_1 . (a_0-w_{s,x}) . p_s$
α_0	$(a_0-w_{s,x}) / (b_0-w_{s,y}) \leq 2$	$(b_0-w_{s,y}) / (a_0-w_{s,x}) \leq 2$

Note 1:

F'_1 : $F_1' = 0,5 \cdot \alpha_0 / (1 + \alpha^4{}_0)$

F'_2 : $F_2' = 0,5 \cdot \alpha^4{}_0 / (1 + \alpha^4{}_0)$

a_0, b_0 : Equivalent dimensions of the panel as defined in [5.1.4], in m

$w_{s,x}$, $w_{s,y}$: Wide base of stiffeners as shown in Fig 4, in m

p_S : Local pressure, in kN/m² as defined in Sec 2, [2.2]

5.3 Bending moments and transverse shear forces for bottom panel under slamming loads

5.3.1 General

The bending moments and transverse shear forces induced by slamming loads are to be calculated as defined in [5.2.1] and [5.2.2], taking into account a lateral pressure, in kN/m², equal to:

$p_s = p_{sl} \cdot K_{DA}$

where:

p_{sl} : Slamming load under bottom, in kN/m² as defined in Sec 2, [2.2]

K_{DA} : Dynamic amplification coefficient defined in [5.3.2].

5.3.2 Dynamic amplification coefficient K_{DA}

For panel built in composite materials, the bottom slamming loads may be increased by an amplification factor taking into account the rigidity of the panel.

This dynamic amplification is mainly significant for sandwich composite panels and is not, as a general rule, to be taken into account for monolithic panels.

The dynamic amplification coefficient, K_{DA}, is defined in Tab 5.

where:

t_0 : Pulse rise time, in s, obtained from the following formula:

$$t_0 = 0,03\sqrt{\frac{L}{43}}$$

with:

L : Rule length of the ship, in m, as defined in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2])

T : Sandwich panel proper period, in s, equal to:

$$T = 1/(C_m f)$$

with:

C_m : $C_m = \dfrac{1}{\sqrt{1 + \dfrac{m_0}{W}}}$

m_0 : $m_0 = \rho_w \dfrac{1}{\pi\sqrt{\dfrac{1}{a^2} + \dfrac{1}{b^2}}}$

a , b : Sides of the sandwich panel in X and Y direction respectively, in m, measured as shown in Fig 5

ρ_W : Water mass density, in general to be taken equal to 1025 kg/m³

W : Sandwich weight per square metre, in kg/m², as defined in [2.1.5]

f : Proper frequency of the sandwich panel, in Hz, equal to:

$$f = \frac{\pi}{2a^2}\sqrt{\frac{1}{W10^3}}\sqrt{5,14D_{11} + 3,13(D_{12} + 2D_{33})\alpha^2 + 5,14D_{22}\alpha^4}$$

α : Aspect ratio equal to a/b

D_{ij} : As defined in [2.3], in N·mm²/mm.

Table 5 : Coefficient K_{DA}

Type of laminate	t_0/T	K_{DA}
Monolithic	NA	1
Sandwich	$t_0/T < 0,9$	$0,98\left(1+\frac{\sin(\pi t_0/T)}{\pi t_0/T}\right)$
	$0,9 \le t_0/T \le 2$	1,1
	$2 < t_0/T$	1
Note 1: $(\pi t_0/T)$ is expressed in rad in the formula of K_{DA}		

5.4 Bending moments and transverse shear forces for side shell panel under impact pressure

5.4.1 General

The bending moments and shear forces induced by impact pressure on side shell are to be calculated as defined in [5.4.3] and [5.4.4], taking into account a lateral pressure, in kN/m², equal to:

$p_s = p_{ssmin} \cdot C_p \cdot \cdot K'_{DA}$

where:

p_{ssmin} : Impact pressure on side shell, in kN/m², as defined in Sec 2, [2.2]

K'_{DA} : Dynamic amplification coefficient defined in [5.4.2]

C_p : Coefficient given in Tab 6.

5.4.2 Dynamic amplification coefficient K'_{DA}

For panel built in composite materials, the impact load on side shell may be increased by an amplification factor taking into account the rigidity of the panel.

This dynamic amplification is mainly significant for sandwich composite panels and is not, as a general rule, to be taken into account for monolithic panels.

The dynamic amplification coefficient, K'_{DA}, is to be taken equal to the amplification coefficient K_{DA} defined in [5.3.2], taking into account the following parameters:

t_0 : Pulse rise time equal to 0,01s

T : Sandwich panel proper period, in s, equal to: $T = 1/f$

with:

f : Proper frequency of the sandwich panel, in Hz, as defined in [5.3.2].

Table 6 : Bending moments under side shell impact pressure

	$a \ge 0,6$ m $b \ge 0,6$ m	$a \ge 0,6$ m $b < 0,6$ m	$a < 0,6$ m $b \ge 0,6$ m	$a < 0,6$ m $b < 0,6$ m
M_x	$\frac{-0,36P_s}{24a_0}\frac{(3a_0^2-0,36)}{T_b}F_xK_{s,x}$	$\frac{-0,6b_0P_s}{24a_0}\frac{(3a_0^2-0,36)}{T_b}F_xK_{s,x}$	$\frac{-0,6P_s}{12T_b}a_0^2F_xK_{s,x}$	As defined in [5.2.1] with C_p=1 for the calculation of p_s defined in [5.4.1]
M_y	$\frac{-0,36P_s}{24b_0}\frac{(3b_0^2-0,36)}{T_a}F_yK_{s,y}$	$\frac{-0,6P_s}{12T_a}b_0^2F_yK_{s,y}$	$\frac{-0,6a_0P_s}{24b_0}\frac{(3b_0^2-0,36)}{T_a}F_yK_{s,y}$	
M'_x	$\nu_y E_x M_y/E_y$			
M'_y	$\nu_x E_y M_x/E_x$			
C_p	0,8	$-0,98b^2 + 0,3b + 0,95 \ge 0,8$	$-0,98a^2 + 0,3a + 0,95 \ge 0,8$	

Note 1:

$F_x = b_0^3/(a_0^3+b_0^3)$

$F_y = a_0^3/(a_0^3+b_0^3)$

$T_a = 0.6 + 0.15\, b_0 \le a_0$ and $T_b = 0.6 + 0.15\, a_0 \le b_0$

$K_{s,x}$, $k_{s,y}$: Reduction factor as defined in [5.1.4]b)

a, b : Dimensions of the panel, in m, as defined in [5.1.3]

a_0, b_0 : Equivalent dimensions of the panel, in m, as defined in [5.1.4], a)

a' : Minimum value of a or b

Note 2: The sign of the moments are to be chosen in order to respect the traction and compression faces of the laminate under lateral pressure, as shown on Fig 5.

5.4.3 Bending moments calculation

The bending moments induced by impact pressure p_s, defined in [5.4.1], on side shell are to be obtained, per metre width of laminate, in kN·m/m, as defined in Tab 6.

5.4.4 Transverse shear forces calculation

The transverse shear forces T_{xz} and T_{yz} , induced by impact pressure on side shell, are to be obtained, in kN per metre width of laminate, in kN/m, from the following formulae:

$T_{xz} = T_{yz} = 0,6.p_{st} / 4$

where:

p_{st} : Impact pressure on side shell, in kN/m², equal to $p_{ssmin}.K'_{DA}$

5.5 Bending moments and transverse shear forces calculation for deck panel under wheeled loads

5.5.1 The wheeled forces, the number of wheels and the type print area of wheels are to be indicated by the Designer.

As a rule, the bending moments and transverse shear forces for panel under wheeled loads are to be determined by direct calculations, submitted by the Designer for examination.

The panel analysis is to be carried out as defined in [5.1.2].

5.6 Bending moments and transverse shear forces calculation for side shell panel under lateral ice loads

5.6.1 The bending moments and transverse shear forces for side shell panel located in the reinforced ice belt hull and subjected to ice loads are to be calculated as defined in Sec 3, [10.4].

6 Rule analysis of panel under global loads

6.1 General

6.1.1 Application and global loads

All panels contributing to the longitudinal hull strength (and to the transverse strength, for catamaran) and submitted to global bending and/or global shear stresses are to be checked according the present Article.

The global loads considered are the global hull girder loads induced by still water and wave loads, resulting in forces and moment acting on the ship along its whole length (and its whole breadth, for catamaran).

These global loads are defined in Sec 2, [3.2].

6.1.2 Analysis and scantling criteria

The panel scantling is to be examined under in plane compressive and/or tensile forces and under in plane shear forces deduced from the global strength analysis defined in Sec 2, [3].

The main scantling criteria to be checked are:

a) Maximum stress in each layer

The maximum stresses in each layer of the panel laminate induced by in-plane forces due to global loads are to satisfy the following criteria:

$\sigma \leq \sigma_{br} / SF$

$\tau \leq \tau_{br} / SF$

where:

σ, τ : Local stresses in individual layers induced by in-plane global loads and calculated as defined in [3.2.3]

σ_{br}, τ_{br} : Theoretical breaking stresses of layers as defined in Sec 5

SF : Minimum rule safety factor as defined in Sec 2, [1.3.2].

b) Combined stress in each layer

The combined criterion SF_{CS} is to be in compliance with the equation defined in Sec 2, [1.3.3].

c) Laminate buckling

The laminate buckling, based on a global laminate panel analysis, is to satisfy the following criteria:

$\sigma_a \leq \sigma_c / SF_B$

where:

σ_a : Compression stress applied to the whole panel and calculated as defined in Sec 2, [4.2.2]

σ_c : Critical buckling stresses of the panel as defined in Article [4]

SF_B : Minimum buckling rule safety factor as defined in Sec 2, [1.3.4].

6.1.3 Analysis and scantling criteria where a finite element model is carried out

A calculation report is to be submitted by the Designer for examination and has to include for the different loading cases considered, the following information:

- reaction forces and moments in way of the model boundary conditions
- forces in the elements modelled with rods
- stresses in the element modelled with shell elements
- mesh size of the highly stressed area.

The main scantling criteria to be checked are defined in [6.1.2] taking into account:

- for maximum stress in each layer:

  σ and τ : Actual stresses in individual layers, in the considered local ply axis, induced by in-plane global loads and deduced from the 3D finite element model, including out of plane shear stress

- for combined stress in each layer:

  σ_i and τ_{12}: Actual stresses in individual layers, in the considered local ply axis, induced by in-plane global loads and deduced from the 3D finite element model

- for laminate buckling:

  σ_a : Actual compression stress applied to the whole panel, induced by in-plane global loads and deduced from the 3D finite element model

  σ_c : Ultimate buckling stress calculated according to [4] or by finite element software. In this case, the software values are to be documented by the Designer.

7 Rule analysis of panel under global and local loads combined

7.1 Application

7.1.1 Application and loads

When panel scantling is checked taking into account lateral pressures combined with global loads, the present Article is applicable.

The local bending moments and shear forces induced by lateral pressures are to be calculated according to [5.2] for the local sea pressure and internal pressures only.

The main stresses induced by the global hull girder loads (still water and wave loads, resulting in forces and moment acting on the ship along its whole length, and its whole breadth, for catamaran) are to be calculated according to Sec 2, [4] and Sec 2, [5].

7.1.2 Analysis and scantling criteria

The panel analysis is carried out by a “ply by ply” analysis of the laminate and buckling of the global laminate.

The main scantling criteria to be checked are:

a) Maximum stress in each layer:

   The main stresses in each layer of the panel laminate are to be in compliance with the following criteria:

   $\sigma \leq \sigma_{br} / SF$

   $\tau \leq \tau_{br} / SF$

   where:

   σ : Actual local bending stress in each layer induced by the local bending moment plus the global hull girder loads calculated according to [7.1.3]

   τ : Actual local shear stress in each layer induced by the local shear force induced by the local force as defined in [3.3.2] and [7.1.3].

   σ_{br} , τ_{br} : Theoretical breaking stresses of layers as defined in Sec 5

   SF : Safety factor as defined in Sec 2, [1.3].

b) Combined stress in each layer:

   The combined criterion SF_{CS} is to be in compliance with the equation defined in Sec 2, [1.3.3], where the actual stresses σ_1 and σ_2 are defined in [7.1.3].

c) Laminate buckling:

   The laminate buckling, based on a global laminate panel analysis, is to satisfy the following criteria:

   $\sigma_a \leq \sigma_c / SF_B$

   where:

   σ_a : Compression stress applied to the panel and calculated as defined in Sec 2, [4.2.2]

   σ_c : Critical buckling stresses of the panel as defined in Article [4]

   SF_B : Minimum buckling rule safety factor as defined in Sec 2, [1.3.4].

7.1.3 Bending moments, shear forces and in plane forces distributions

The actual stresses in each layer σ_1, σ_2, τ_{13} and τ_{23} at each side of the laminate (as shown on Fig 5), induced by the local bending moment and shear force and the global loads, may be calculated as defined in [3.2.3] and [3.3.2], with the following terms of the load matrix:

a) In case of global loads is applied in the direction X of the panel:

1) At point B of side b of the laminate:

N_X : Tensile or compressive force, in kN/m, induced by the global loads in X direction to be taken equal to:

$N_x = \sigma_A . t . 10^3$

where:

σ_A : Stress applied to the panel and calculated as defined in Sec 2, [4.2.2]

t : Laminate thickness, in mm

N_y : Tensile or compressive force, in kN/m, induced by Poisson's effect in Y direction to be taken equal to:

$N_y = N_x . \nu_x . E_y / E_x$

where:

ν_x : Poisson's ration in X direction of the panel as defined in [2.2.1]

E_x, E_y : Tensile moduli, in N/mm² in X and Y direction of the panel as defined in [2.2.1]

M_x : Main local bending moment, in kNm, around Y axis calculated at the middle of the panel boundary b, as defined in Tab 3

M'_y : Secondary local bending moment, in kNm, around X axis calculated at the middle of the panel boundary b, to be taken equal to M'_y in Tab 3

T_{yz} : Main local shear force, in kN/m, calculated at the middle of the panel boundary b, as defined in Tab 4

2) At point A of side a of the laminate:

N_X, N_y : Tensile or compressive force, in kN/m, as defined in 1)

M_y : Main local bending, in kNm, around X axis calculated at the middle of the panel boundary a, as defined in Tab 3

M'_x : Secondary local bending moment, in kNm, around Y axis calculated at the middle of the panel boundary a, to be taken equal to M'_x in Tab 3

T_{xz} : Main local shear force, in kN/m, calculated at the middle of the panel boundary a, as defined in Tab 4

b) In case of global loads is applied in the direction Y of the panel:

1) At point B of side b of the laminate:

N_y : Tensile or compressive force, in kN/m, induced by the global loads in Y direction to be taken equal to:

$N_y = \sigma_A . t . 10^3$

where:

σ_A : Stress applied to the panel in Y direction Sec 2, [4.2.2]

t : Laminate thickness, in mm

N_x : Tensile or compressive force, in kN/m, induced by Poisson's effect in YX direction to be taken equal to:

$N_x = N_y . \nu_y . E_x / E_y$

where:

ν_y : Poisson's ration in Y direction of the panel as defined in [2.2.1]

E_x, E_y : Tensile moduli, in N/mm² in X and Y direction of the panel as defined in [2.2.1]

M_x, M'_y and T_{yz}:As defined in item a) 1).

2) At point A of side a of the laminate:

N_x, N_y : Tensile or compressive force, in kN/m, as defined in 1)

M'_x, M_y and T_{yz}:As defined in item a) 2).

Section 7 Stiffener Analysis

1 General

1.1 Application

1.1.1 Basic elements definition

In the present Section, basic elements refer to the different laminate elements making up the stiffener, i.e the attached plating, the web and the flange

1.1.2 The purpose of the present Section is to define the rule analysis of the secondary and primary stiffeners under local and global loads, as defined in Sec 2, [2.2] and Sec 2, [3.2].

The rule scantling of stiffeners is based on the:

- deformation analysis of each basic element
- stress calculation in each layer of the laminates of the basic elements making up the stiffener, and
- check of the stress safety factors
- buckling where applicable.

The following parameters are to be taken into account to characterise a stiffener:

- geometry of the stiffener
- main characteristics of the laminates of the basic elements making up the stiffener (flange, web and attached plating)
- orientation of the individual layers in the laminates of the basic elements in relation to the stiffener global axes.

1.1.3 Laminates making up the basic elements

The main characteristics of the basic elements are to be estimated as defined in Sec 6 for laminates.

The rule scantling of stiffeners is based on the following simplifying hypothesis:

- the flange, web and attached plating are considered as homogeneous materials
- the local strains of the flange and of the attached plating under stiffener bending are considered as uniform over their thickness.

1.1.4 Stiffener rule analysis under local external loads

Stiffeners submitted to local external loads as defined in [4.1.1] are examined under local bending moments and shear forces with a "ply by ply" theoretical analysis.

The local distribution of strains and the values of the stresses in each ply of laminate basic elements depend on the:

- type of individual layers
- orientation of the individual layers in relation to the longitudinal axis of the stiffeners
- dimensions of the stiffener.

1.1.5 Stiffener rule analysis under global loads

Stiffeners submitted to global loads as defined in [5.1.1] are mainly examined with:

- buckling analysis, considering the global rigidity of the stiffener and the dimensions of the basic elements
- ply by ply analysis under axial forces.

As a rule, the stiffener rule analysis under global loads is to be carried out when a global strength analysis according to Sec 2, [3] is required.

1.1.6 Stiffener rule analysis under local external loads combined with global loads

Stiffeners submitted to local external loads combined with global loads as defined in [6.1.2] are mainly examined with:

- buckling analysis, considering the global rigidity of the stiffener and the dimensions of the basic elements
- ply by ply analysis considering the local bending moments and shear forces and the global axial forces.

As a rule, the stiffener rule analysis under local external loads and global loads is to be carried out when deemed necessary by the Society.

1.2 Stiffener model analysis

1.2.1 Isolated beam model

The requirements for the scantling of stiffeners defined in the present Section apply for isolated beam calculation.

1.2.2 Two or three dimensional primary stiffener model

When an isolated beam calculation of the primary structure is not possible due to an interaction of the primary stiffeners, a two- or three-dimensional structural model analysis including the different primary stiffeners is to be carried out as follows:

a) Model:

The structural model is to represent the primary supporting members, with their attached plating of the structure area considered.

The extension of the structural model is to be such that the results in the areas to be analysed are not influenced by the unavoidable inaccuracy in the modelling of the boundary conditions.

b) Loading conditions:

The local lateral pressures to be considered are:

- for bottom primary stiffeners: sea pressures and bottom slamming pressures (when slamming may occur)
- for side shell and, for multihull, primary transverse cross structure of platform bottom: sea pressures (without taking into account side shell impact)
- for deck primary stiffeners: external or internal pressures, minimum loads and when applicable, wheeled loads
- for all primary stiffeners, when applicable: internal pressures.

When deemed necessary, it may be taken into account of the counteraction between the internal and external loads in the most severe conditions.

Note 1: When a bottom slamming pressure analysis is carried out for planing hull, the impact pressure is to be only applied on one floor of the model as a constant pressure. The other floors of the model are to be loaded by the bottom sea pressure.

c) Checking criteria:

The scantling criteria are defined in [4.1.3].

1.2.3 Two or three dimensional primary stiffener finite element model

a) Finite elements

In order to obtain an accurate representation of stresses in the areas of interest, the structural model is to be built on the basis of the following criteria:

- the mesh dimensions are to be such as to enable a faithful representation of the stress gradients
- quadrilateral elements are to have 90° angles as much as possible, or angles between 60° and 120°
- the use of linear triangular elements is to be avoided as much as possible in high stress area. When the use of a linear triangular element cannot be avoided, its edges are to have the same length
- the use of membrane and rod elements is only allowed when significant bending effects are not present; in the other cases elements with general behaviour (quadratic finite element acting in traction, compression and bending and bar element acting also in bending) are to be used
- webs of primary members are to be modelled with at least three elements on their height
- the ratio between the longer side and the shorter side of elements is to be less than 3 in the areas expected to be highly stressed.
- large openings in web of primary supporting members and door openings in bulkheads are to be correctly represented taking into account local reinforcement when provided.

b) Load model

The finite element model is to be loaded taking into account the local loads defined in applicable Society’s Rules for the classification.

Distributed loads are to be applied:

- to the plating panels when the platings are modelled by shell elements (quadratic finite element acting in traction, compression and bending) and the secondary stiffeners by bar elements (acting also in bending), or
- directly to the primary supporting members actually supporting the secondary stiffeners proportionally to the areas of influence of secondary stiffeners.

c) Boundary conditions:

The finite element calculation is to be performed with displacement restrictions applied to nodes of the model.

As a rule these nodes are to be located outside the model areas where stress checks are carried out.

Detailed justifications may be requested by the Society to verify that the forces reactions applied to these nodes do not affect the bending moments and shear forces applied to the model.

d) Document to be submitted

A document setting the hypothesis considered for the calculation model is to be submitted by the Designer for examination. This document is to include:

- a complete representative hull structure model geometry specifying for the different members their main characteristics (materials, mechanical characteristics, scantling)
- the orientation of the shell element co-ordinate system in relation to the reference co-ordinate system of the model and the co-ordinate system of the fibre orientations
- the boundary conditions applied to the model

- the loads distribution
- the reference of the finite element analysis programs used by the Designer.
- the mesh size of the highly stressed areas.

e) Checking criteria

The scantling criteria are defined in Sec 6, [6.1.3].

1.3 Stiffener calculation methodology

1.3.1 Rule scantling

The methodology to review the minimum rule scantling criteria of secondary and/or primary stiffener, based on an isolated beam approach, is defined in Tab 1.

1.3.2 Structural models

When a two- or a three-dimensional beam model calculation is carried out for the review of a primary structure, the stiffeners may be modelled with the characteristics as defined in Article [10].

Table 1 : Methodology

Step	Description	Refer to
1	Calculation of the geometric characteristics, rigidity and theoretical breaking stresses of each individual layer of the laminates of the basic elements in their local orthotropic axes	Sec 5
2	Geometrical description of the laminates of each basic element to define the: • position of all the individual layers • orientation of each layer in relation to the longitudinal axe of the stiffener	Sec 6, [2.1.2] and Sec 6, [2.1.3]
3	Calculation, for each basic element, of the global elastic coefficients and the mechanical characteristics of the laminates, in the stiffener axes	Sec 6, [2.2]
4	Calculation of the stiffener characteristics	[2.2]
5	For stiffener under local loads: • calculation of the bending moment M and the shear force T • calculation of the stresses in each individual layer of the laminates of each basic element in the stiffener longitudinal axes, induced by M and T	[4] and [3.1.1]
6	For stiffeners under global loads: • calculation of the global stress in the transverse section of the stiffener • calculation of the stresses in each individual layer of the laminates of each basic element, in the stiffener longitudinal axe and in its own local axes • calculation of the critical buckling stress	Sec 2, [4.2.1] and [3.2.1] and [3.2.2]
7	For stiffener under local loads combined with global loads: Calculation of the combined stresses in each individual layer of the laminate of each basic element induced by local and global loads	[6]
8	Check of the scantling criteria under local loads and overall resistance, when applicable	[4.1.3] and [5.1.2] and [6]

2 Stiffener basic characteristics

2.1 General

2.1.1 The basic elements of a stiffener are to be considered taking into account their:

- global tensile modulus E_X and in-plane shear modulus G_{XY}, defined in Sec 6, [2.2.1], in the longitudinal direction of the stiffener
- dimensions and thicknesses
- global neutral axis position V_{Xi}, as defined in Sec 6, [2.2.2].

2.1.2 Attached plating

The width of the attached plating to be taken into account for calculation of the stiffener characteristics is defined, for secondary and primary stiffeners, in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

Where the attached plating is a sandwich laminate, its global tensile modulus is to be calculated without taking into account the sandwich core.

2.2 Stiffener characteristics

2.2.1 Neutral axis for bending analysis

The neutral axis V, in mm, of a stiffener is to be obtained, for the bending analysis, from the following formula:

$$V = \frac{\sum E_{Xi} \cdot S_i \cdot Z_{Xi}}{\sum E_{Xi} \cdot S_i}$$

where:

E_{Xi} : Modulus of each basic element of the stiffener, in N/mm², in the longitudinal direction of the stiffener, calculated according to Sec 6, [2.2.1]

S_i : Section of each basic element of the stiffener, in mm²

Z_{Xi} : Distance, in mm, between the outer face of the attached plating and the neutral axis of each basic element of the stiffener (see Fig 1).

2.2.2 Distance between the attached plating and flange to neutral axis

The distance between the neutral axis of the attached plating V_{plat} and the neutral axis of the flange N_{fl}, in mm, to the neutral axis of the stiffeners are to be obtained from the following formula:

$$V_{plat} = V - \frac{t_{plat}}{2}$$

$$N_{fl} = \left(t_{plat} + t_{reinf} + h_{web} + \frac{t_{fl}}{2}\right) - V$$

where:

t_{plat} : Thickness, in mm, of the attached plating

t_{fl} : Thickness, in mm, of the flange

h_{web} : Height, in mm, of the web

V : Neutral axis position, in mm, as defined in [2.2.1].

2.2.3 Global tensile modulus of stiffener

The global tensile modulus E, in N/mm², of a stiffener in its longitudinal axis is equal to:

$$E = \frac{\sum E_{Xi} \cdot S_i}{\sum S_i}$$

where:

E_{Xi} : Main moduli in the longitudinal axis of the stiffener elements (associated plate, web and flange), in N/mm², as defined in Sec 6, [2.2.1]

S_i : Section, in mm², of the associated plate, web and flange of the stiffener.

2.2.4 Global bending rigidity and inertia of stiffener

The rigidity, in N·mm², of the stiffener in its longitudinal axis is given by the following formula:

$$[EI] = \sum E_{Xi} \cdot (I_i + S_i \cdot d_i^2)$$

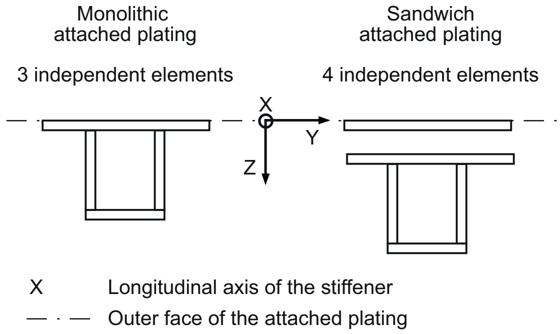
where:

d_i : Distance, in mm, between the neutral axis of each basic element of the stiffener and the neutral axis of the stiffener: $d_i = Z_{Xi} - V$

S_i : Section, in mm², of each basic element of the stiffener

I_i : Proper inertia of each basic element of the stiffener, in mm⁴, in relation to the horizontal axis Y of the stiffener (see Fig 1).

Figure 1 : Stiffener model



3 Stiffener behaviour under bending moments, shear forces and axial forces

3.1 Stiffener behaviour under bending moment and shear forces

3.1.1 Strains and stresses induced by bending moments and shear forces

a) Strains:

The bending strains ε_{xi} of the attached plating and of the flange, and the shear strain γ_{xy} of the web, in %, induced by the bending moment and shear force due to local loads are calculated as follows:

$$\varepsilon_{xi} = \frac{M \cdot d_i}{[EI]} \cdot 10^8$$

$$\gamma_{xy} = \frac{T}{\sum S_i \cdot G_{XY}} 10^5$$

where:

M : Bending moment, in kN·m, applied to the stiffener, as defined in [4.2]

d_i : As defined in [2.2.4] for the attached plating and for the flange

[EI] : Global bending rigidity, in N/mm², as defined in [2.2.4]

T : Shear force, in kN, applied to the stiffener, as defined in [4.2]

S_i : Shear area of the web, in mm²

G_{XY} : In-plane shear modulus of the web, in N/mm², as defined in Sec 6, [2.2.1].

Note 1: Attention is to be paid to the sign of the bending moment M which conditions the type of stresses (tensile or compression) in the attached plating and in the flange of the stiffener.

Note 2: In order to simplify the stiffener scantling review, the strains and the tensile or compression stresses induced by the bending moment are only determined in the attached plating and in the flange of the stiffener, and are neglected in the web.

b) Stresses in the individual layers:

The bending local stresses, in N/mm², in each layer of the laminates of the attached plating and of the flange and the shear stresses, in N/mm², in each layer of the web, in their local axes, are given by the following formulae:

$$\sigma_1 = (\bar{R}_{11} \cdot \varepsilon_1 + \bar{R}_{12} \cdot \varepsilon_2)/100$$

$$\sigma_2 = (\bar{R}_{21} \cdot \varepsilon_1 + \bar{R}_{22} \cdot \varepsilon_2)/100$$

$$\tau_{12} = (\bar{R}_{33} \cdot \gamma_{12})/100$$

where:

R_{11} , R_{12} , R_{21} , R_{22} , R_{33} : Elements of the matrix of rigidity defined for each layer in Sec 5, [4.1.1]

ε_1 , ε_2 , γ_{12} : Strains equal to:

- for attached plating and flange:

  $\varepsilon_1 = (\cos\theta)^2 \cdot \varepsilon_{xi}$

  $\varepsilon_2 = (\sin\theta)^2 \cdot \varepsilon_{xi}$

  $\gamma_{12} = -2 \cdot \sin\theta \cdot \cos\theta \cdot \varepsilon_{xi}$

- for web:

  $\varepsilon_1 = \sin\theta \cdot \cos\theta \cdot \gamma_{xy}$

  $\varepsilon_2 = -\sin\theta \cdot \cos\theta \cdot \gamma_{xy}$

  $\gamma_{12} = [(\cos\theta)^2 - (\sin\theta)^2] \cdot \gamma_{xy}$

with:

ε_{xi} , γ_{xy} : Strains in each basic element of the stiffener, calculated as defined in item a).

Note 3: θ is the orientation of an individual layer in relation to the longitudinal axis X of the stiffener, as shown in Fig 1.

3.2 Stiffener behaviour under axial forces

3.2.1 Strain and stresses induced by axial forces

a) Stress and strain in stiffener:

The global stress σ_A, in N/mm², and strain ε_A, in %, in the stiffener in its longitudinal axis induced by axial forces are to be calculated as follow:

$$\sigma_A = \frac{E}{100} \varepsilon_{Aref}$$

$$\varepsilon_A = \frac{100}{E} \sigma_A$$

where:

E : Global tensile modulus of the stiffener, in N/mm² as defined in [2.2.3]

ε_{Aref} : Overall longitudinal strain, in %, as defined in Sec 2, [4.2.1]

b) Strain and stresses in the basic elements of the stiffener:

The global stress σ_{Ai}, in N/mm², and strain ε_{Ai}, in %, in the basic elements of the stiffener in the longitudinal axis of the stiffener are to be calculated as follow:

$$\sigma_{Ai} = \frac{E_i}{100}\varepsilon_{Aref}$$

$$\varepsilon_{Ai} = \frac{100}{E_i}\sigma_{Ai}$$

where:

E_i : Main Young moduli of the associated plate, web and flange, in the longitudinal axis of the stiffener, in N/mm², as defined in Sec 6, [2.2.1]

ε_{Aref} : Overall longitudinal strain, in %, as defined in Sec 2, [4.2.1].

c) Stresses in the individual layers:

The local stresses, in N/mm², in each layer of the laminates of the basic elements, in their local axes are given by the following formulae:

$$\sigma_1 = (\bar{R}_{11} \cdot \varepsilon_1 + \bar{R}_{12} \cdot \varepsilon_2)/100$$

$$\sigma_2 = (\bar{R}_{21} \cdot \varepsilon_1 + \bar{R}_{22} \cdot \varepsilon_2)/100$$

$$\tau_{12} = (\bar{R}_{33} \cdot \gamma_{12})/100$$

where:

$\varepsilon_1 = (\cos\theta)^2 \cdot \varepsilon_{Aref}$

$\varepsilon_2 = (\sin\theta)^2 \cdot \varepsilon_{Aref}$

$\gamma_{12} = -2 \cdot \sin\theta \cdot \cos\theta \cdot \varepsilon_{Aref}$

with:

ε_{Aref} : Overall longitudinal bending strain, in %, as defined in Sec 2, [4.2.1].

3.2.2 Critical buckling stress under axial forces

The buckling modes considered for stiffener under axial forces are the global column buckling and the local buckling of web or flange.

a) Global column buckling:

The critical column buckling stress is obtained, in N/mm², from the following formula:

$$\sigma_c = \pi^2\frac{[EI]}{S\ell^2}10^{-6}$$

where:

[EI] : Global bending rigidity, in N.mm², as defined in [2.2.4] or in [10.1.3] a)

S : Global sectional area, in mm², of the stiffener with its associated plate

ℓ : Span, in m, of the stiffener.

b) Local buckling of web or flange:

The critical local buckling stress of web of stiffener is obtained, in N/mm², from the following formula:

- web of stiffener without flange:

$$\sigma_c = 0{,}8\left(\frac{t_w}{h_w}\right)^2 E_{xw}$$

- web of stiffener with flange:

$$\sigma_c = 3{,}8\left(\frac{t_w}{h_w}\right)^2 E_{xw}$$

where:

t_w, h_w : Thickness and height of the web, in mm

E_{xw} : Tensile modulus of the web in the longitudinal axis of the stiffener, in N/mm², as defined in Sec 6, [2.2.1].

- flange:
  - for T flange:

$$\sigma_c = 0{,}8\left(\frac{t_f}{b_f}\right)^2 E_{xf}$$

- for omega flange:

$$\sigma_c = 3{,}8\left(\frac{t_f}{b_f}\right)^2 E_{xf}$$

where:

t_f, b_f : Thickness and breadth of the flange, in mm

E_{xf} : Tensile modulus of the flange in the longitudinal axis of the stiffener, in N/mm², as defined in Sec 6, [2.2.1].

4 Rule analysis of stiffeners under local loads

4.1 General

4.1.1 Application and local loads

All the stiffeners sustaining lateral loads are to be checked according to the present Article.

As a general rule, the bending moments and shear forces applied to the stiffeners are to be calculated according to [4.2] for the following lateral pressures:

- sea pressures
- bottom slamming loads when applicable
- impact pressure on side shell (for secondary stiffener only)
- internal pressures
- wheeled loads
- ice loads on side shell when applicable.

These local pressures, defined in Sec 2, [2.2], are to be calculated:

- for horizontal stiffeners: at mid-span of the stiffener considered
- for vertical stiffeners: at the lower and upper levels of the stiffener considered.

4.1.2 Calculation parameters

a) Ends conditions:

The bending moment value of a stiffener depends on the degree of freedom at its ends.

The end conditions are taken into account by means of a coefficient m, taken equal to:

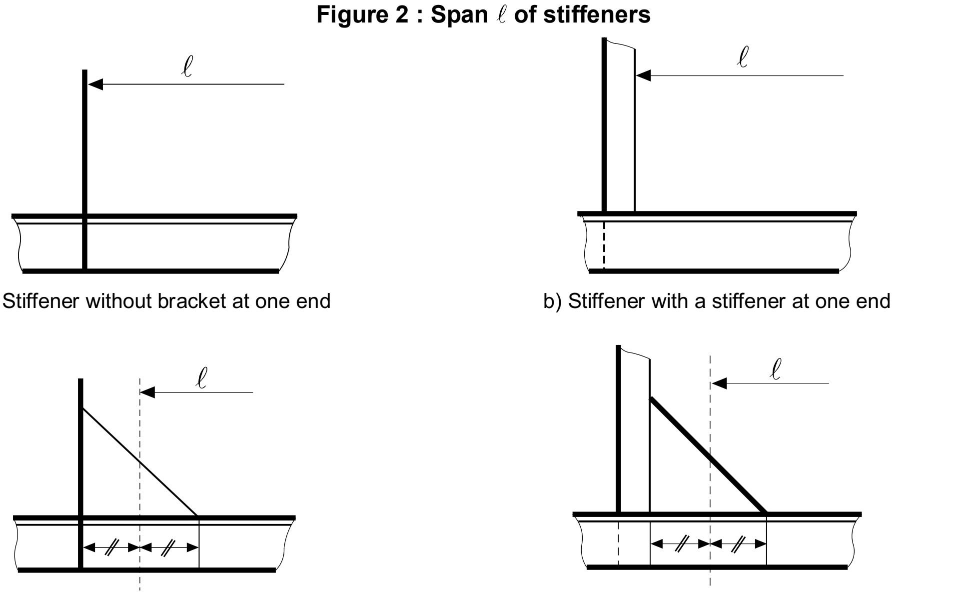
- when the cross-section at the ends of the stiffener cannot rotate under the effect of lateral loads (fixed ends): m = 12
- when the cross-section at the ends of the stiffener can rotate freely under the effect of lateral loads (simply supported ends): m = 8
- when the cross-section at the ends of the stiffener is in an intermediate condition between fixed end condition and simply supported end condition: m = 10.

b) Span of stiffeners:

The span ℓ of the stiffeners is to be measured as shown from Fig 2.

For open floors, when a beam calculation taking into account the rigidity of the two transverse stiffeners is not carried out, the span ℓ of the transverse secondary stiffeners connected by one or two struts is to be taken equal to 0,7 ℓ_2 according to Fig 3.

Figure 2 : Span ℓ of stiffeners



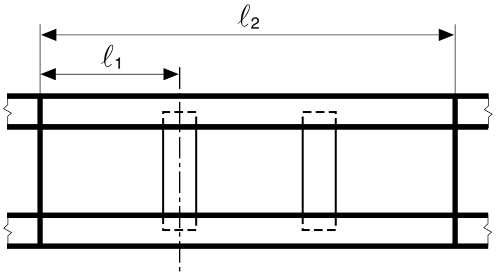
a) Stiffener without bracket at one end

b) Stiffener with a stiffener at one end

c) Stiffener with a bracket at one end

d) Stiffener with a bracket and a stiffener at one end

Figure 3 : Span of stiffeners in case of open floors



4.1.3 Analysis and scantling criteria

The stiffener analysis is carried out by a "ply by ply" analysis of the layers of the basic elements according to [3.1.1] b), taking into account the bending moment M and the shear force T defined in [4.2].

The main scantling criteria to be checked are:

a) Maximum stress in each layer:

The main stresses in each layer of the laminates of the basic elements are to be in compliance with:

$\sigma_i \leq \sigma_{br} / SF$

$\tau_i \leq \tau_{br} / SF$

σ_i, τ_i : Stresses applied in each layer calculated as defined in [3.1.1] b)

σ_{br}, τ_{br} : Theoretical breaking stresses of layers as defined in Sec 5

SF : Safety factors as defined in Sec 2, [1.3].

b) Combined stress in each layer:

The combined criterion SF_{CS} is to be in accordance with the equation defined in Sec 2, [1.3.3], where:

Note 1: Attention is to be paid on the location where the strains are calculated along the stiffener length.

At the ends of a stiffener loaded by an external pressure:

- the flange is to be in compression (negative strain)
- the attached plating is to be in tensile (positive strain).

At the mid-span of a stiffener loaded by an external pressure:

- the flange is to be in tensile (positive strain)
- the attached plating is to be in compression (negative strain).

4.2 Bending moment and shear force calculation

4.2.1 Bending moment and shear force calculation for stiffeners under sea or internal pressures

The bending moment M, in kN·m, and the shear force T, in kN, of the horizontal and vertical stiffeners subjected to lateral local pressures are to be obtained from the following formulae:

- for horizontal stiffeners (longitudinal and transverse):

$$M = C_f \frac{p \cdot s \cdot \ell^2}{m}$$

$$T = C_t \frac{p \cdot s \cdot \ell}{2}$$

- for vertical stiffeners:

$$M = C_f \frac{p_1 \cdot s \cdot \ell^2}{m_1}$$

$$T = C_t \frac{p_2 \cdot s \cdot \ell}{m_2}$$

where:

ℓ : Span of the stiffener, in m, measured as indicated in [4.1.2] b)

s : Spacing between stiffeners, in m

p : Local sea pressure or internal pressure, in KN/m², as defined in the applicable Society Rules defined in Sec 1, [1.1.2]

p_1 , p_2 : Equivalent pressure, in KN/m², as defined in Tab 2

C_f and C_t: Reduction coefficients to be taken equal to:

$$C_f = 1 - 0,25\left(\frac{s}{\ell}\right)^2 - 0,2\left(\frac{s}{\ell}\right)$$

$$C_t = 1 - \frac{s}{2\ell}$$

with C_f and C_t to be taken greater than 0,55

m : m = 12, 10 or 8 depending on the end conditions, as defined in [4.1.2] a)

m_1, m_2 : End stiffener condition coefficients defined in Tab 2.

Table 2 : Equivalent pressures

End stiffener condition	P_1	m_1	P_2	m_2
Both ends fixed	$2\ p_{Supper} + 3\ p_{Slower}$	60	$3\ p_{Supper} + 7\ p_{Slower}$	20
Lower end fixed, upper end supported	$7\ p_{Supper} + 8\ p_{Slower}$	120	$9\ p_{Supper} + 16\ p_{Slower}$	40
Both ends supported	$p_{Supper} + p_{Slower}$	16	$p_{Supper} + 2\ p_{Slower}$	6
Note 1: p_{slower} ,p_{supper}, : Sea pressure or internal pressure calculated at lower end of the stiffener and at upper end of the stiffener respectively, in KN/m², as defined in the applicable Society Rules defined in Sec 1, [1.1.2].				

4.2.2 Bending moment and shear force calculation for stiffeners under slamming loads

The bending moment M, in kN·m, and the shear force T, in kN, of the bottom stiffeners subjected to bottom slamming loads are to be obtained as defined in [4.2.1] taking into account the bottom impact pressure defined in the Society Rules for the classification and or certification (see Sec 1, [1.1.2]).

4.2.3 Secondary stiffeners under side shell impacts

As a rule, the bending moment M, in kN·m, and the shear force T, in kN, of the horizontal and vertical secondary stiffeners sustaining lateral side shell impacts are to be obtained from the following formulae:

$$M = C_f \frac{p \cdot s \cdot \ell^2}{m}$$

$$T = C_t \frac{p \cdot s \cdot \ell}{2}$$

where:

p : Pressure, in KN/m², to be taken equal to:

$p = C_p \,.\, p_{ssmin}$

C_p : Pressure coefficient equal to:

$C_p = -0{,}98s^2 + 0{,}3s + 0{,}95 \geq 0{,}8$

ℓ : Span of the stiffener, in m, measured as indicated in [4.1.2] b)

s : Spacing between stiffeners, in m, not to be taken greater than 0,6 for the calculation of M and T

m : m = 12, 10 or 8 depending on the end conditions, as defined in [4.1.2] a)

p_{ssmin} : Impact pressure on side shell, in KN/m², as defined in the applicable Society Rules defined in Sec 1, [1.1.2]

C_f and C_t: Reduction coefficients to be taken equal to:

$C_f = 0{,}3\ (3\ \ell^2 - 0{,}36) / \ell^3$ with $\ell \geq 0{,}6$m

$C_t = 0{,}6 / \ell$ without being greater than 1.

4.2.4 Bending moment and shear force calculation for stiffeners under wheeled loads

The wheeled forces, the number of wheels and the type print area of wheels are to be indicated by the Designer.

As a rule, the bending moments and transverse shear forces for stiffeners under wheeled loads are to be determined by direct calculations, submitted by the Designer for examination.

The stiffener analysis is to be carried out as defined in [3.1].

5 Rule analysis of stiffeners under global loads

5.1 General

5.1.1 Application and global loads

All the stiffeners contributing to the longitudinal strength (and to the transversal strength for catamaran) and submitted to global bending and/or global shear stresses are to be checked according to the present Article.

The global loads considered are the global hull girder loads induced by still water and wave loads, resulting in forces and moment acting on the ship along its whole length (and along its whole breadth for catamaran).

The global loads are defined in Sec 2, [3.2].

5.1.2 Analysis and scantling criteria

Three main scantling criteria are to be checked in each element of the stiffener, regarding:

- maximum stress in each layer
- combined stress in each layer
- global column buckling and local buckling of web.

a) Maximum stress in each layer:

The maximum stresses in each layer of the elements of the stiffener induced by in-plane forces due to global loads are to satisfy the following criteria:

$\sigma_i \leq \sigma_{br} / SF$

$\tau_i \leq \tau_{br} / SF$

where:

σ_i, τ_i : Local stresses in individual layers of each element of the stiffener induced by in-plane global loads and calculated as defined in [3.2.1] c)

σ_{br}, τ_{br} : Theoretical breaking stresses of layers as defined in Sec 5

SF : Minimum rule safety factor as defined in Sec 2, [1.3.2].

b) Combined stress in each layer

The combined criterion SF_{CS} is to be in compliance with the equation defined in Sec 2, [1.3.3].

c) Stiffener buckling:

The buckling stiffener is to satisfy the following criteria:

$\sigma_a \leq \sigma_c / SF_B$

where:

σ_a : Compression stress applied to the stiffener and calculated as defined in Sec 2, [3.3]

σ_c : Critical global column buckling and critical local buckling of web stresses as defined in [3.2.2]

SF_B : Minimum buckling rule safety factor as defined in Sec 2, [1.3.4].

6 Rule analysis of stiffeners under global and local loads combined

6.1 Application

6.1.1 Application and loads

When stiffener scantling is checked taking into account lateral pressures combined with global loads, the present Article is applicable.

The local stresses induced by the bending moments and shear forces due to lateral pressures are to be calculated according to [3.1] for the local sea pressure and internal pressures only.

The main stresses induced by the global hull girder loads (still water and wave loads, resulting in forces and moment acting on the ship along its whole length, and its whole breadth, for catamaran) are to be calculated according to [3.2].

6.1.2 Analysis and scantling criteria

Three main scantling criteria are to be checked in each element of the stiffener, regarding:

- maximum stress in each layer
- combined stress in each layer
- global column buckling and local buckling of web.

a) Maximum stress in each layer:

The maximum stresses in each layer of the elements of the stiffener induced by in-plane forces due to global loads and bending moment induced by local loads are to satisfy the following criteria:

$\sigma \leq \sigma_{br} / SF$

$\tau_{12} \leq \tau_{br} / SF$

where:

σ : Sum of stresses in individual layers of each element of the stiffener induced by local bending moment (as defined in [3.1.1] b) and global loads (as in [3.2.1] c))

τ_{12} : Local shear stresses in individual layers of the web of the stiffener as defined in [3.1.1] b)

σ_{br}, τ_{br} : Theoretical breaking stresses of layers as defined in Sec 5

SF : Minimum rule safety factor as defined in Sec 2, [1.3.2].

b) Combined stress in each layer

The combined criterion SF_{CS} is to be in compliance with the equation defined in Sec 2, [1.3.3], where the actual stresses σ_1 and σ_2 are to be taken as the sum of stresses in individual layers of each element of the stiffener induced by local bending moment (as defined in [3.1.1] b) and global loads (as in [3.2.1] c)).

c) Stiffener buckling:

The buckling stiffener is to satisfy the following criteria:

$\sigma_a \leq \sigma_c / SF_B$

where:

σ_a : Compression stress applied to the stiffener and calculated as defined in [3.2.1] a)

σ_c : Critical global column buckling and critical local buckling of web stresses as defined in [3.2.2]

SF_B : Minimum buckling rule safety factor as defined in Sec 2, [1.3.4].

7 Scantling of brackets at ends of secondary and primary stiffeners

7.1 General requirements

7.1.1 Brackets are to be provided at the stiffener ends when the continuity of the web and the flange of the stiffener is not ensured in way of its supports.

As a general rule, the sectional area and the section modulus of any end bracket are generally to be not less than those of the stiffener supported by the bracket.

7.1.2 When a bracket is provided to ensure the simultaneous continuity of two (or three) stiffeners of equivalent stiffness, the bracket scantling is to be examined by direct calculation, taking into account the balanced bending moment in the connection of the two (or three) stiffeners.

7.1.3 The principle for connection of perpendicular stiffeners located in the same plane or for connection of stiffeners located in perpendicular planes is to be equivalent to:

- for stiffeners in the same plane: as shown in Fig 4
- for stiffeners in perpendicular planes: as shown in Fig 5.

Figure 4 : Connection of stiffeners located in the same plane

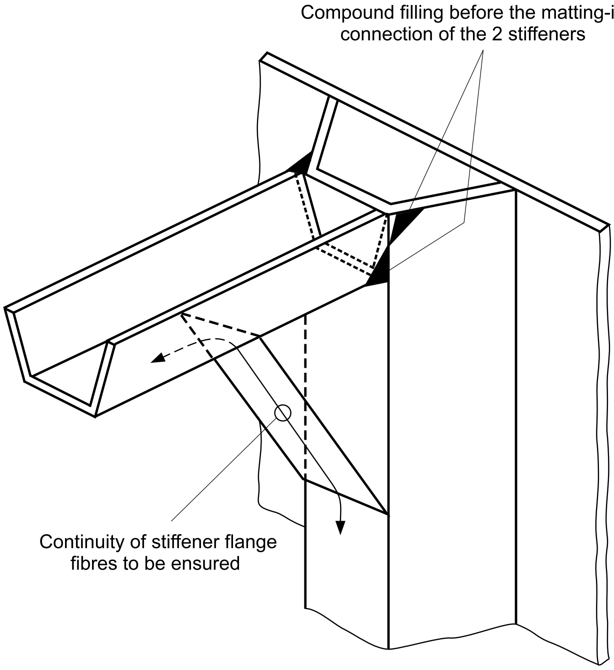
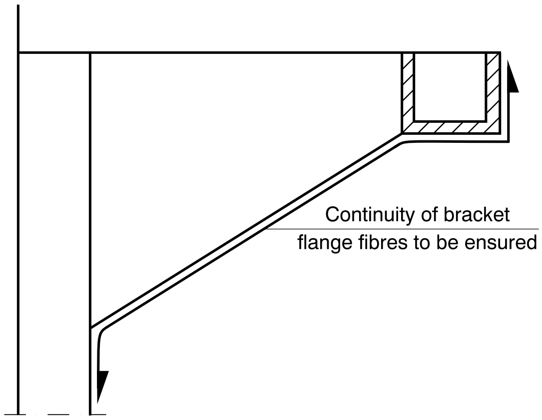


Figure 5 : Connection of stiffeners located in perpendicular planes



8 Large openings in webs of primary stiffeners

8.1 Calculation methodology

8.1.1 In case of large openings in stiffener webs as shown in Fig 6, the secondary stresses in primary supporting members due to the openings are to be considered for the reinforcement of the web.

The secondary stresses may be calculated in accordance with the following procedure, where suffixes 1 and 2 are only used to differentiate the different elements of the members (1) and (2):

a) Members (1) and (2) are subjected to the following secondary force and bending moments:

$$F = \frac{M_A + M_B}{2d}$$

$$m_1 = \left|\frac{M_A - M_B}{2}\right| K_1$$

$$m_2 = \left|\frac{M_A - M_B}{2}\right| K_2$$

where:

M_A , M_B : Bending moments, in kN·m, in sections A and B of the primary supporting member

d : Distance, in m, between the neutral axes of members (1) and (2)

$$K_1 = \frac{E_1 \cdot I_1}{E_1 \cdot I_1 + E_2 \cdot I_2}$$

$$K_2 = \frac{E_2 \cdot I_2}{E_1 \cdot I_1 + E_2 \cdot I_2}$$

with:

I_1 , I_2 : Moments of inertia, in cm^4, of members (1) and (2) with their attached plating

E_1 , E_2 : Young moduli, in N/mm^2, of members (1) and (2) along the longitudinal axis of the stiffener.

b) Members (1) and (2) are subjected to a uniform compression or tensile strain, in %, equal to:

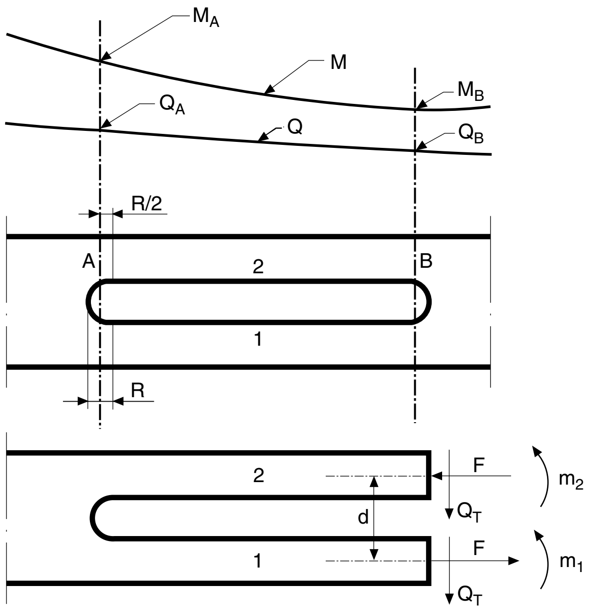
$$\varepsilon_{F1} = \frac{F}{\sum_i (S_i \cdot E_{Xi})_1} 10^5$$

$$\varepsilon_{F2} = \frac{F}{\sum_i (S_i \cdot E_{Xi})_2} 10^5$$

with:

$S(S_i \cdot E_{Xi})_1$, $S(S_i \cdot E_{Xi})_2$: Sums of the product between the section, in mm^2, and the Young modulus, in N/mm^2, of each basic element of members (1) and (2).

Figure 6 : Large opening in primary supporting members - Secondary stresses



c) The flange and attached plating of members (1) and (2) are subjected to a longitudinal bending strain, in %, induced by the secondary bending moments m_1 and m_2, equal to:

$$\varepsilon_{xi1} = \frac{m_1 \cdot d_{i1}}{10 \cdot E_{Xi1} \cdot I_1} 10^2$$

$$\varepsilon_{xi2} = \frac{m_2 \cdot d_{i2}}{10 \cdot E_{Xi2} \cdot I_2} 10^2$$

where:

d_{i1} , d_{i2} : Distances, in mm, between the neutral axis of the basic elements and the neutral axis of members (1) and (2).

d) The web of members (1) and (2) is subjected to a shear strain, in %, induced by the shear force Q_T , equal to:

$$\gamma_{xy1} = \frac{K_1 Q_T}{\sum_i (S_i \cdot G_{XYi})_1} 10^5$$

$$\gamma_{xy2} = \frac{K_2 Q_T}{\sum_i (S_i \cdot G_{XYi})_2} 10^5$$

where:

Q_T : Shear force, in kN, applied to members (1) and (2), and equal to Q_A or Q_B , whichever is the greater

$S(S_i \cdot G_{XYi})_1$, $S(S_i \cdot G_{XYi})_2$: Sums of the product between the section, in mm², and the shear modulus, in N/mm², of the web of members (1) and (2).

K_1 : Coefficient equal to:

$$K_1 = \frac{\sum (S_i G_i)_1}{\sum (S_i G_i)_1 + \sum (S_i G_i)_2}$$

$$K_2 = \frac{\sum (S_i G_i)_2}{\sum (S_i G_i)_1 + \sum (S_i G_i)_2}$$

8.1.2 Analysis and scantling criteria

The local stresses in each layer of the laminates of the basic elements making up the member (1) and (2) (flange, web and attached plating) in way of the large openings are to be in compliance with the scantling criteria defined in [4.1.3].

When stresses do not comply with these scantling criteria, reinforcement layers in web members (1) and (2) and/or reinforcement layers to edge the large opening are to be provided.

9 Analysis of specific stiffeners

9.1 Stiffeners made with plywood and composite materials

9.1.1 Stiffeners made with plywood and composite materials are to be examined as defined in the present Section.

In this case, plywood is to be considered as an elementary layer such as a woven roving with its own mechanical characteristics.

9.2 Curved stiffeners

9.2.1 The curvature of primary supporting members may be taken into account by direct analysis.

In case of 2D or 3D beam structural model, the curved primary supporting members may be represented by a number N of straight beams, N being adequately selected to minimize the spring effect in way of knuckles.

When the angle between two successive straight beams is not more than 3°, the stiffness of knuckle equivalent springs is considered as not modifying the local bending moment and shear force distribution.

9.3 Custom section stiffeners

9.3.1 General

Custom section stiffeners are defined by an association of elements. Those elements are constituted of segments which are defined by a laminate and end points.

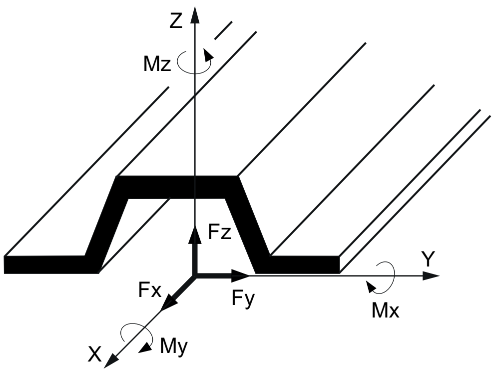
Tensile and shear rigidity of the section are identical to tensile and shear rigidity of equivalent sections built with elements with identical characteristics and the ending points of the composite material section as described in [10.2].

The equivalent sections may be loaded with internal forces and moments defined in [9.3.2].

The deformation induced by the loads are defined in [9.3.3].

When custom section stiffener is used, a specific attention is to be paid to the sufficient bracketing of the stiffener at its ends.

Figure 7 : Reference co-ordinate system for custom section stiffeners



9.3.2 Loads

Custom shape stiffeners may be loaded with internal forces and moments F_x, F_y, F_z, M_x, M_y and M_z as defined in Fig 7.

9.3.3 Deformation

Deformation due to each loads are to be calculated independently based on corresponding equivalent section as defined in [9.3.1] where:

- Deformation due to F_x:

$$\varepsilon_x = \frac{F_x}{A_x \times E_{x-ref}}$$

Where:

A_x : Cross-sectional area, in mm², of the stiffener

E_{x-ref} : Arbitrary reference Young modulus value chosen for the section reference, in N/mm²

- Deformation due to F_z:

$$\gamma_{xy} = \frac{\tau_{ref}}{G_{xy-ref}}$$

With τ_{ref}, the shear stress, in N/mm² of the equivalent stiffener due to F_z force defined as:

$$\tau_{ref} = \frac{F_z \cdot m}{2 \cdot I_y \cdot ep_{ref-i}}$$

Where:

G_{xy-ref} : Arbitrary reference Shear modulus value chosen for the section reference, in N/mm^2

m : Distance between neutral axis of the equivalent stiffener and the centre of gravity of the considered element

I_y : Inertia, in mm^4, of the equivalent stiffener

ep_{ref-i} : Thickness, in mm, of the considered element of the stiffener.

- Deformation due to F_y:

$$\gamma_{xy} = \frac{\tau_{ref}}{G_{xy-ref}}$$

With τ_{ref}, the shear stress, in N/mm^2 of the equivalent stiffener due to F_z force defined as:

$$\tau_{ref} = \frac{F_y \cdot m}{2 \cdot I_x \cdot ep_{ref-i}}$$

Where:

G_{xy-ref} : Arbitrary reference Shear modulus value chosen for the section reference, in N/mm^2

m : Distance between neutral axis of the equivalent stiffener and the centre of gravity of the considered element

I_x : Inertia, in mm^4, of the equivalent stiffener

ep_{ref-i} : Thickness, in mm, of the considered element of the stiffener.

- Deformation due to M_x:

$$\varepsilon_x = \frac{M_x \times d_{zi}}{I_y \times E_{x-ref}}$$

Where:

d_{zi} : Horizontal distance between vertical neutral axis and the considered calculation point

I_x : Inertia, in mm^4, of the equivalent stiffener

E_{x-ref} : Arbitrary reference Young modulus value chosen for the section reference, in N/mm2

- Deformation due to M_z:

$$\varepsilon_x = \frac{M_z \times d_{yi}}{I_z \times E_{x-ref}}$$

Where:

d_{yi} : Vertical distance between horizontal neutral axis and the considered calculation point

I_z : Inertia, in mm^4, of the equivalent stiffener

E_{x-ref} : Arbitrary reference Young modulus value chosen for the section reference, in N/mm^2

- Deformation due to M_y:

$$\gamma_{xy} = \frac{\tau}{G_{ref}}$$

where:

τ : Shear stress due to St Venant torsion load M_y

10 Stiffener characteristics for 2D or 3D beam model

10.1 Stiffener parameters

10.1.1 When a beam model calculation in two or three dimensions is carried out, the tensile, bending, shear and torsional rigidities may be calculated according to the present Article, with the following symbols:

E_{Xi} : Tensile modulus, in N/mm^2, calculated according to Sec 6, [2.2.1] in relation to the global longitudinal stiffener axis, of the attached plating (E_{Xplat}) and its reinforcement when applicable (E_{Xplatr}), the web (E_{Xweb}), the flange (E_{Xfl}) and its reinforcement when applicable (E_{Xflr})

A_i : Cross-sectional area, in mm^2, of the attached plating (A_{plat}) and its reinforcement when applicable (A_{platr}), the web (A_{web}), the flange (A_{fl}) and its reinforcement when applicable (A_{flr})

G_{XYi} : Plane shear modulus, in N/mm^2, in their own local axes XY, calculated according to Sec 6, [2.2.1] of the attached plating (G_{XYplat}) and its reinforcement when applicable ($G_{XYplatr}$), the web (G_{XYweb}), the flange (G_{XYfl}) and its reinforcement when applicable (G_{XYflr})

The dimensions of the elements of the stiffener are defined as follow, according to Fig 8:

d_i : Distance, in mm, between the neutral axis of the stiffener and the centre of gravity of the attached plating (d_{plat}) and its reinforcement when applicable (d_{platr}), the web (d_{web}), the flange (d_{fl}) and its reinforcement when applicable (d_{flr})

t_i : Thickness, in mm, of the attached plating (t_{plat}) and its reinforcement when applicable (t_{platr}), the web (t_{web}), the flange (t_{fl}) and its reinforcement when applicable (t_{flr})

In the following formulae, t_{web} for stiffener of omega type and t_{flr} for reinforcement on flat stiffener are to be taken equal to the thickness of one element only as shown on Fig 8, excepted where specified

h_i : Height, in mm, of the web (h_{web}) and of the reinforcement for flat stiffener, when applicable (h_{flrr})

b_i : Breath, in mm, of the attached plating (b_{plat}) and its reinforcement when applicable (b_{platr}), the flange or the reinforcement for flat stiffener when applicable (b_{fl}).

10.1.2 Tensile and shear rigidity

a) The tensile rigidity of a stiffener, in N, according to its longitudinal axis x may be calculated as follows:

$$[E_X A_X] = \sum E_{Xi} \cdot A_i$$

b) The shear rigidity of a stiffener, in N, according to its transversal axis y may be calculated as follows:

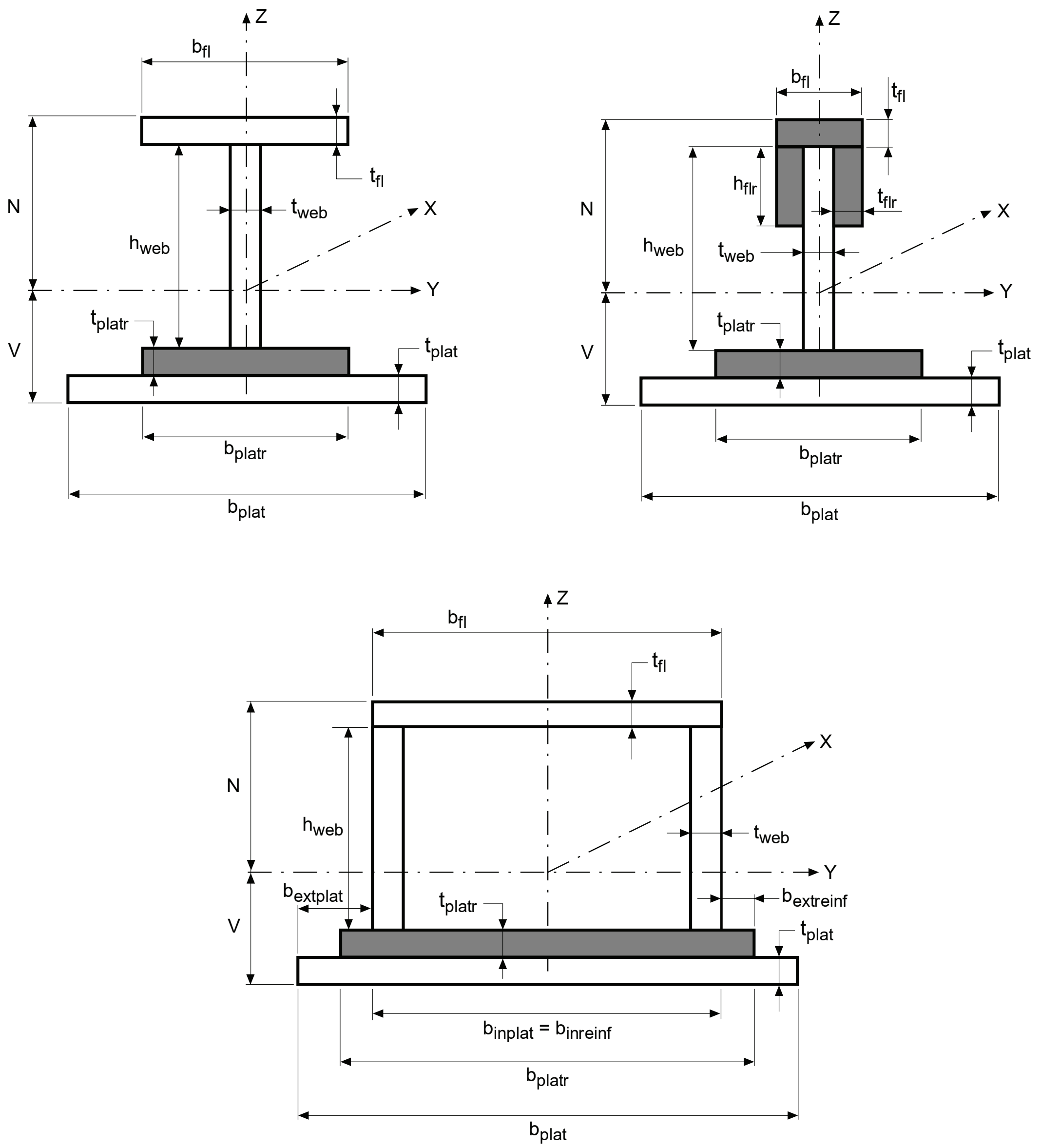
$$[G_Y A_Y] = \frac{5}{6}(G_{XYfl} \cdot A_{fl} + G_{XYplat} \cdot A_{plat} + G_{XYplatr} \cdot A_{platr})$$

c) The shear rigidity of a stiffener, in N, according to its vertical axis z may be calculated as follows:

$$[G_Z A_Z] = \frac{5}{6} G_{XYweb} A_{web}$$

Note 1: For stiffeners of omega type, t_{web} is to be taken as the thickness of the two webs for the calculation of A_{web}.

Figure 8 : Stiffener characteristics



10.1.3 Bending rigidity

a) The bending rigidity of a stiffener, in Nmm^2, in relation to the Y axis of the stiffener may be calculated as follows:

$$[E_X I_Y] = E_{Xfl} \cdot I_{Yfl} + E_{Xweb} \cdot I_{Yweb} + E_{Xplat} \cdot I_{Yplat} + E_{Xplatr} \cdot I_{Yplatr} + E_{Xflr} \cdot I_{Yflr}$$

where:

$$I_{Yfl} = \frac{b_{fl} \cdot t_{fl}^3}{12} + A_{fl} \cdot d_{fl}^2$$

$$I_{Yflr} = 2\left(\frac{t_{flr} \cdot h_{flr}^3}{12} + A_{flr} \cdot d_{flr}^2\right)$$

$$I_{Yplatr} = \frac{b_{platr} \cdot t_{platr}^3}{12} + A_{platr} \cdot d_{platr}^2$$

$$I_{Yweb} = \frac{t_{web} \cdot h_{web}^3}{12} + A_{web} \cdot d_{web}^2$$

$$I_{Yplat} = \frac{b_{plat} \cdot t_{plat}^3}{12} + A_{plat} \cdot d_{plat}^2$$

Note 1: For stiffeners of omega type, t_{web} is to be taken as the thickness of the two webs for the calculation of I_{Yweb}.

b) The bending rigidity of a stiffener, in Nmm^2, in relation to the Z axis of the stiffener may be calculated as follows:

$$[E_X I_Z] = E_{Xfl} \cdot I_{Zfl} + E_{Xweb} \cdot I_{Zweb} + E_{Xplat} \cdot I_{Zplat} + E_{Xplatr} \cdot I_{Zplatr} + E_{Xflr} \cdot I_{Zflr}$$

where:

$$I_{Zfl} = \frac{t_{fl} \cdot b_{fl}^3}{12}$$

$$I_{Zflr} = 2\left(\frac{h_{flr} \cdot t_{flr}^3}{12} + A_{flr} \cdot \left(\frac{b_{fl} - t_{flr}}{2}\right)^2\right)$$

$$I_{Zplat} = \frac{t_{plat} \cdot b_{plat}^3}{12}$$

$$I_{Zplatr} = \frac{t_{platr} b^3_{platr}}{12}$$

- for stiffener of T, angle or flat type:

$$I_{Zweb} = \frac{h_{web} \cdot t_{web}^3}{12}$$

- for stiffener of omega type:

$$I_{Zweb} = 2\left[\frac{h_{web} \cdot t_{web}^3}{12} + h_{web} \cdot t_{web}\left(\frac{b_{fl} - t_{web}}{2}\right)^2\right]$$

10.1.4 Torsional rigidity

a) For stiffeners of T, angle or flat type, the torsional rigidity, in Nmm^2, may be calculated as follows:

$$[G_X I_X] = G_{XYfl} \cdot I_{Xfl} + G_{XYweb} I_{Xweb} + G_{XYplat} I_{Xplat} + G_{XYfl} I_{Xfl} + G_{XYplatr} I_{Xplatr} + G_{XYflr} \cdot I_{Xflr}$$

where:

$$I_{Xplat} = \frac{b_{plat} \cdot t_{plat}^3}{3}$$

$$I_{Xplatr} = \frac{b_{platr} t^3_{platr}}{3}$$

$$I_{Xweb} = \frac{h_{web} \cdot t_{web}^3}{3}$$

$$I_{Xfl} = \frac{b_{fl} \cdot t_{fl}^3}{3}$$

$$I_{xflr} = 2\frac{h_{flr} \cdot t_{flr}^3}{3}$$

b) For stiffeners of omega type, the torsional rigidity, in Nmm^2, may be calculated as follows:

$$[G_X I_X] = G_{Xmoy} \cdot \left[I_{Xbox} + \frac{2}{3} \cdot I_{plat}\right]$$

where G_{Xmoy} , I_{plat} and I_{Xbox} are defined in Tab 3.

10.1.5 Eccentricity

The eccentricity e_Y and e_Z equal to the distance between the centre of gravity and the shear centre of the stiffener, in mm, may be estimated as specified in Tab 4.

Table 3 : Torsional rigidity parameters

G_{Xmoy}	$G_{Xmoy} = \dfrac{2G_{Xweb}h_{web}t_{web} + G_{Xfl}b_{fl}t_{fl} + G_{Xplat}b_{plat}t_{plat} + G_{Xplatr}b_{platr}t_{platr}}{2h_{web}t_{web} + b_{fl}t_{fl} + b_{plat}t_{plat} + b_{platr}t_{platr}}$
I_{plat}	$I_{plat} = b_{extplat} \cdot \left[t_{plat} \cdot \dfrac{G_{XYplat}}{G_{Xmoy}}\right]^3 + b_{extreinf} \cdot \left[t_{platr} \cdot \dfrac{G_{XYplatr}}{G_{Xmoy}}\right]^3$
I_{Xbox}	$I_{Xbox} = \dfrac{4\Omega^2}{\dfrac{b_{fl}}{t_{fl}\dfrac{G_{XYfl}}{G_{Xmoy}}} + \dfrac{2h_{web}}{t_{web}\dfrac{G_{XYweb}}{G_{Xmoy}}} + \dfrac{b_{inplat}}{t_{plat}\dfrac{G_{XYplat}}{G_{Xmoy}} + t_{platr}\dfrac{G_{XYplatr}}{G_{Xmoy}}}}$

Note 1:

$$\Omega = \left[b_{fl} - t_{web}\frac{G_{XYweb}}{G_{Xmoy}}\right]\left[h_{web} + \frac{t_{plat}G_{XYplat}}{2G_{Xmoy}} + \frac{t_{fl}G_{XYfl}}{2G_{Xmoy}} + \frac{t_{platr}G_{XYplatr}}{2G_{Xmoy}}\right]$$

Table 4 : Eccentricity of stiffener shear centre

e_Y	$e_Y = 0$
e_Z	$e_Z = \dfrac{E_{Xfl} \cdot I_{Zfl}\left(\dfrac{t_{fl}}{2} + h_{web} + t_{plat} + t_{platr}\right) + 2E_{Xflr} \cdot I_{Zflr}\left(t_{plat} + t_{platr} + h_{web} - \dfrac{h_{flr}}{2}\right) + \dfrac{t_{plat}}{2} \cdot E_{Xplat} \cdot I_{Zplat} + \left(\dfrac{t_{platr}}{2} + t_{plat}\right) \cdot E_{Xplatr} \cdot I_{Zplatr}}{E_{Xfl} \cdot I_{Zfl} + 2E_{Xflr} \cdot I_{Zflr} + E_{Xplat} \cdot I_{Zplat} + E_{Xplatr} \cdot I_{Zplatr}} - V$

Note 1:

V : Distance between the neutral axis of the stiffener, as defined in [2.2.1], and the external face of the attached plating.

10.2 Stiffener parameters for custom section stiffeners

10.2.1 Elements analysis

Each element seg_i is defined with two nodes with:

- coordinates $\{y_i ; z_i\}$
- a length ℓ_i
- Center of gravity coordinates $\{y_{CoG-i}, z_{CoG-i}\}$
- thicknesses equal to:
  - for bending and shear analysis (F_x, F_y, F_z, M_x, M_z):

$$ep_{ref-i} = \frac{ep_{comp-i} \times E_{x-comp-i}}{E_{x-ref}}$$

  - for torsional analysis (M_y):

$$ep_{tors-i} = \frac{ep_{comp-i} \times G_{xy-comp-i}}{G_{xy-ref}}$$

where:

ep_{comp-i}, $G_{xy-comp-i}$, $E_{x-comp-i}$:Element laminates basic characteristics calculated according to Sec 6, [2]

E_{x-ref}, G_{xy-ref}: Arbitrary reference Young and Shear modulus values chosen for the section reference, in N/mm^2.

10.2.2 Neutral axes

The neutral axes V_y and V_z, in mm, of a stiffener are to be obtained, for the bending analysis, from the following formulae:

- For horizontal neutral axis V_z:

$$V_z = \frac{\sum E_{xi} \cdot S_i \cdot z_i}{\sum E_{xi} \cdot S_i}$$

- For vertical neutral axis V_y:

$$V_y = \frac{\sum E_{xi} \cdot S_i \cdot y_i}{\sum E_{xi} \cdot S_i}$$

where:

E_{xi} : Young modulus of each basic element of the stiffener, in N/mm², in the longitudinal direction of the stiffener, calculated according to Sec 6, [2.2.1]

S_i : Section of each basic element of the stiffener, in mm²

z_i : z coordinates of neutral axis of element i projected on vertical axis, in mm.

y_i : y coordinates of neutral axis of element i projected on horizontal axis, in mm.

10.2.3 Tensile and shear rigidity

a) The tensile rigidity of a stiffener, in N, according to its longitudinal axis x may be calculated as follows:

$$E_x A_x = A_{x-ref} \cdot E_{x-ref}$$

where:

$$A_{x-ref} = \sum \ell_i \times ep_{ref-i}$$

b) The shear rigidity of a stiffener, in N, according to its vertical axis z may be calculated as follows:

$$G_{xy} A_z = A_{z-ref} \cdot G_{xy-ref}$$

where:

$$A_{z-ref} = \sum \ell_{i-ver} \times ep_{ref-i}$$

$\ell_{i\text{-}ver}$: Segment vertical projected length

$$\ell_{i-ver} = |z_{node-i} - z_{node-i+1}|$$

c) The shear rigidity of a stiffener, in N, according to its horizontal axis y may be calculated as follows:

$$G_{xy} A_y = A_{y-ref} \cdot G_{xy-ref}$$

where:

$$A_{y-ref} = \sum \ell_{i-hor} \times ep_{ref-i}$$

$\ell_{i\text{-}hor}$: Segment vertical projected length

$$\ell_{i-hor} = |y_{node-i} - y_{node-i+1}|$$

10.2.4 Bending rigidity

a) The bending rigidity of a stiffener, in N.mm², in relation to y axis of the stiffener may be calculated as follows:

$$E_x I_y = I_{y-ref} \cdot E_{x-ref}$$

where:

$I_{y\text{-}ref}$: Moment of inertia of the equivalent section in relation to y axis, in mm⁴

b) The bending rigidity of a stiffener, in N.mm², in relation to z axis of the stiffener may be calculated as follows:

$$E_x I_z = I_{z-ref} \cdot E_{x-ref}$$

where:

$I_{z\text{-}ref}$: Moment of inertia of the equivalent section in relation to z axis, in mm⁴

10.2.5 Torsional rigidity

The torsional rigidity of a stiffener, in N.mm², in relation to x axis of the stiffener may be calculated as follows:

$$G_{xy} I_x = I_{x-ref} \cdot G_{ref}$$

where:

$I_{x\text{-}ref}$: Moment of inertia of the equivalent section in relation to x axis. $I_{x\text{-}ref}$ may be defined as follows:

- for closed or partially closed transverse section

$$I_{x-ref} = \frac{4\Omega^2}{\sum (\ell_i / ep_{tors-i})}$$

where:

Ω : Section, in mm² of the closed part of the section.

- for open transverse section

$$I_{x-ref} = \sum \left(\frac{\ell_i \cdot ep_{tors}}{3} \right)^3$$

10.2.6 Excentricity

The eccentricity e_Y and e_Z equal to the distance between the centre of gravity and the shear centre of the stiffener, in mm, is to be taken into account in case of grillage model.

11 Stiffener connection with attached plate

11.1 Connection by bonded angle

11.1.1 General

The stiffeners are to be connected to their attached plating by bonding angles on both side of the stiffener webs.

As a rule, the total bonding angles are to have:

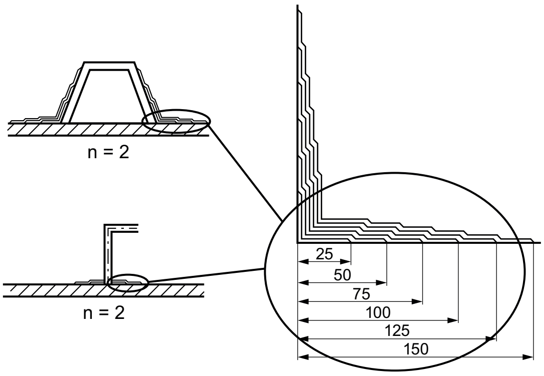
- the same shear rigidity by length unit [$G_i e_i$], in N/mm, than the stiffener web, where:

  G_i : Shear modulus, in N/mm², of the stiffener web or the bonding angle

  e_i : Thickness, in mm, of the stiffener web or the sum of bonding angles

- an overlap as shown on Fig 9.

Figure 9 : Overlap of stiffener bonding angle



11.1.2 Direct calculation

The scantling and overlap length of stiffener bonding angles may be checked by direct calculation as follow:

a) Bonding angle scantling:

The shear stresses in each layer of the bonding angle are to be in compliance with:

$\tau_i \leq \tau_{br} / SF.C_{ab}$

where:

τ_{br} : Theoretical shear breaking stresses of layers as defined in Sec 5

SF : Safety factor as defined in Sec 2, [1.3].

C_{ab} : Safety factor taking into account the fabrication process of the bonding angle and to be taken equal to:

- 1,25 in case of hand lay up process
- 1,15 in case of vacuum process

τ_i : Stresses, in N/mm², applied in each layer of the bonding angle in its own local axes calculated for a shear strain in the bonding angle γ_{ab}, in %, equal to:

$$\gamma_{ab} = \frac{T' 10^2}{G_{ab} t_{ab}}$$

T′ : Shear force per unit length, in N/mm, in the bonding angle equal to:

$$T' = \frac{Tm}{n[EI]}$$

T : Shear force, in N, in the stiffener section considered

m : Geometric parameter, in Nmm, equal to: $m = t_{plat}.b_p.V_{plat}.E_{plat}$

t_{plat}, b_{plat} : Thickness and breadth, in mm, of the associated plating

V_p : Distance, in mm, between the inner face of the attached plating where the stiffener is bonded and the neutral axis of the stiffener

E_{plat} : Tensile modulus of the attached plating as defined in Sec 6, [2.2.1], in N/mm², in the longitudinal direction of the stiffener

n : Total number of bonding angle between stiffener and attached plating

G_{ab}, t_{ab} : Shear modulus, in N/mm², and thickness, in mm, of the bonding angle

[EI] : Global bending rigidity of the stiffener, in N.mm², as defined in [2.2.4]

b) Minimum overlap of bonding angle:

The minimum breath ℓ_{ab}, in mm, of each bonded angle on the attached plating may be checked by direct calculation as follow:

$$\ell_{ab} = \frac{T' SF}{\tau_{br}}$$

where:

τ_{br} : Minimum value of:

- Shear breaking stress, in N/mm², of the bonding resin as defined in Sec 4, [5.2], or
- Minimum theoretical breaking stress value τ_{IL}, in N/mm², of the first layer of the attached plating or web or bonding angle as defined in Sec 5, [5.1.1], or
- Shear breaking stress, in N/mm², measured on representative test samples.

SF : Safety factor to be taken equal to: SF = 2,4 C_F

C_F : Coefficient taking into account the laminating process, and generally taken equal to:

- 1,4 in case of a vacuum process with rising curing temperature
- 1,5 in case of vacuum process
- 1,7 in the other cases.

11.2 Connection by adhesive joint

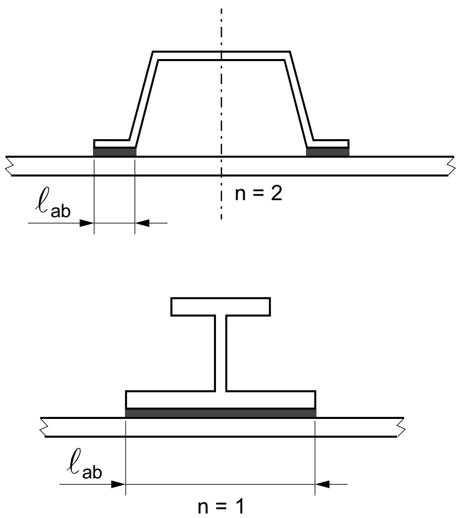
11.2.1 The minimum breath ℓ_{ab}, in mm, of the adhesive joint on the attached plating, as shown in Fig 10, is to be not less than the value defined in [11.1.2] b), where:

τ_{br} : Minimum value of:

- Shear breaking stress, in N/mm², of the adhesive joint as defined in Sec 4, [5.2], or
- Minimum theoretical breaking stress value τ_{IL}, in N/mm², of the first layer of the attached plating or web as defined in Sec 5, [5.1.1], or
- Shear breaking stress, in N/mm², measured on representative test samples taking into account the real production conditions (environmental, surface treatments,...).

n : Number of adhesive joints (see Fig 10)

Figure 10 : Breath ℓ_{ab}



Section 8 Scantling of Pillars in Composite Materials

1 General

1.1 Application

1.1.1 The requirements of this Section apply to pillars (independent profiles or bulkheads stiffeners) made of composites.

1.1.2 The present Section only deals with the buckling and compression check of pillars (the general requirements relating to pillar arrangement are given in Sec 3).

1.1.3 Calculation approach

The scantling check of pillars under axial loads is to be examined under compression axial load defined in [1.1.5] and according to the following methods:

- local main stresses in each layer of the different basic elements induced by the axial load (see [3.1.3])
- global column buckling (see [3.1.4])
- local buckling of the different basic elements (see [3.1.5]).

When deemed necessary, the check of pillar may take into account, in addition to the axial loads, the bending moments at the upper end and at the lower end of the pillar. As a rule, the bending moments are to be deduced from a 2D or 3D beam calculation, and the scantling check is to be carried out as defined in [3.2].

1.1.4 Definition

In the present section, basic element of a pillar refers to a part of laminate characterized by its dimensions and mechanical properties.

Pillars in composite material may be made up of only one basic element (for circular tubular pillars), or of further basic elements (for rectangular tubular or built up pillars).

1.1.5 Compression axial load

Where pillars are vertically aligned, the compression axial load F_A, in kN, is equal to the sum of the loads supported by the pillar considered and those supported by the pillars located above, multiplied by a load factor r.

The load factor depends on the relative position of each pillar with respect to that considered (i.e. the number of tiers separating the two pillars).

The compression axial load in the pillar is to be obtained, in kN, from the following formula:

$$F_A = A_D \cdot p_s + p_L + \sum_i r \cdot Q_i$$

where:

A_D : Area, in m², of the portion of the deck or the platform supported by the pillar considered

p_s : Pressure on deck, in kN/m², as defined in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2])

p_L : Local loads, in kN, if any

r : Load factor depending on the relative position of each pillar above the one considered, to be taken equal to:

- $r = 0,9$ for the pillar immediately above the pillar considered
- $r = 0,9^i \geq 0,478$ for the i^{th} pillar of the line above the pillar considered

Q_i : Vertical local load, in kN, supported by the i^{th} pillar of the line above the pillar considered, if any.

2 Pillar basic characteristics

2.1 General

2.1.1 The following basic characteristics of pillars are to be defined:

E : Global tensile modulus of the pillar in its longitudinal axis

E_{Xi} : Tensile modulus of the different basic elements for built up pillars in the longitudinal axis of the pillar

A : Global transverse section of the pillar

[EI] : Global bending rigidity of the pillar in its main axis.

2.1.2 Hollow tubular pillar

The global tensile modulus E, in N/mm², of the laminate of a hollow tubular pillar in its longitudinal axis is to be taken equal as defined in Sec 6, [2.2.1].

The global transverse section A, in mm², is to be taken equal to:

$$A = 0,785(D^2 - d^2)$$

The global bending rigidity [EI], in N.mm², is to be taken equal to:

$$[EI] = 0,05(D^4 - d^4)E$$

where:

D : Outer diameter of the hollow tubular pillar, in mm

d : Inner diameter of the hollow tubular pillar, in mm

E : Global tensile modulus of the pillar in its longitudinal axis, in N/mm².

2.1.3 Built-up pillar

For built-up pillar, the global tensile modulus E and the tensile modulus E_{Xi} of the basic elements of built-up pillars, in N/mm² and the global bending rigidity [EI], in N.mm² are to be calculated as defined in Sec 7, [2.2.3], Sec 6, [2.2.1] and Sec 7, [2.2.4] respectively.

The global transverse section, in mm², is to be taken equal to the sum of the transverse section of each basic elements.

For pillar with non-symmetrical section, the global bending rigidity [EI] is to be determined in the two main axis of the section.

3 Pillar scantling

3.1 Pillar scantling under compression load

3.1.1 Compression stress and strain in the pillar

The global stress σ_A, in N/mm², and strain ε_A, in %, in the pillar in its longitudinal axis induced by axial compression load are to be calculated as follow:

$$\sigma_A = \frac{F_a}{A}10^3$$

$$\varepsilon_A = \frac{\sigma_A}{E}100$$

where:

F_a : Compression axial load in the pillar, in kN, as defined in [1.1.5]

A : Global transverse section of the pillar, in mm² as defined in Article [2]

E : Global tensile modulus of the pillar, in N/mm² as defined in Article [2].

3.1.2 Compression stress and strain in the basic elements of the pillar

The global stress σ_{Ai}, in N/mm², and strain ε_{Ai}, in %, in the basic elements of the pillar in the longitudinal axis of the pillar are to be calculated as follow:

$$\sigma_{Ai} = \frac{E_{Xi}}{100}\varepsilon_A$$

$$\varepsilon_{Ai} = \frac{100}{E_{Xi}}\sigma_{Ai}$$

where:

E_{Xi} : Main moduli of the basic elements, in the longitudinal axis of the stiffener, in N/mm², as defined in Sec 6, [2.2.1]

ε_A : Overall longitudinal strain, in %, as defined in [3.1.1].

3.1.3 Local main stresses in each individual layer

The local stresses, in N/mm², in each layer of the laminates making up the stiffener, in their local axes are given by the following formulae:

$$\sigma_1 = (\bar{R}_{11} \cdot \varepsilon_1 + \bar{R}_{12} \cdot \varepsilon_2)/100$$

$$\sigma_2 = (\bar{R}_{21} \cdot \varepsilon_1 + \bar{R}_{22} \cdot \varepsilon_2)/100$$

$$\tau_{12} = (\bar{R}_{33} \cdot \gamma_{12})/100$$

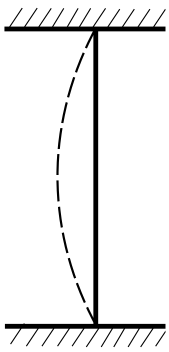
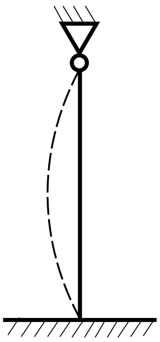
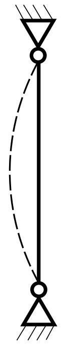
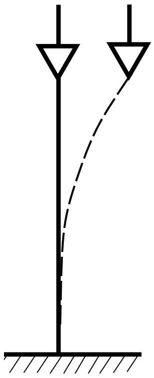
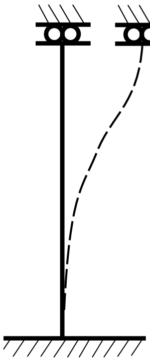
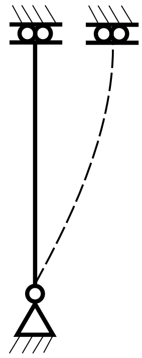
where:

$\varepsilon_1 = (\cos\theta)^2 \cdot \varepsilon_{Ai}$

$\varepsilon_2 = (\sin\theta)^2 \cdot \varepsilon_{Ai}$

$\gamma_{12} = -2 \cdot \sin\theta \cdot \cos\theta \cdot \varepsilon_{Ai}$

Table 1 : Coefficient f

Condition of fixation of the pillar						
Coefficient f	0,5 **(1)**	0,7	1,0	2,0	1,0	2,0
(1) End clamped condition may only be considered when the structure in way of pillar ends can not rotate under the effect of loadings.						

where:

R_{11}, R_{12}, R_{21}, R_{22}, R_{33} : Elements of the matrix of rigidity defined for each layer in Sec 5, [4.1.1]

θ : Orientation of the individual layers in relation to the longitudinal, axis of the pillar

ε_{Ai} : Global compression strain in the basic elements of the pillar, in %, as defined in [3.1.2].

3.1.4 Global column buckling

The critical global column buckling stress σ_{cg}, in N/mm², is determined as follow:

$$\sigma_{cg} = \pi^2 \frac{[EI]}{A(f\ell)^2} 10^{-6}$$

where:

ℓ : Span, in m, of the pillar

f : Coefficient depending on the condition of fixation of the pillars, defined in Tab 1

A : Global transverse section of the pillar, in mm², as defined in Article [2]

[EI] : Global bending rigidity of the pillar in its main axis, in N/mm², as defined in Article [2].

3.1.5 Local buckling

The critical local buckling stresses σ_{cli}, in N/mm², are determined as follow:

- For circular tubular pillars:

$$\sigma_{cl} = 12,5\left(\frac{E}{206000}\right)\left(\frac{t}{D}\right)10^4$$

where:

t : Pillar thickness, in mm

D : Pillar outer diameter, in mm

E : Global tensile modulus of the pillar in its longitudinal axis, in N/mm²

- For rectangular tubular pillars:

$$\sigma_{cli} = 78\left(\frac{E_{Xi}}{206000}\right)\left(\frac{t}{b}\right)^2 10^4$$

where:

b : Greatest dimension of the cross-section, in mm

t : Plating thickness in relation to b, in mm

E_{Xi} : Tensile modulus of the basic elements in relation to b in N/mm²

Note 1: When deemed necessary, it may be necessary to determine σ_{cli} in each side of the rectangular pillar.

- For built up pillars, the lesser of:

$$\sigma_{cli} = 78\left(\frac{E_{Xi}}{206000}\right)\left(\frac{t_W}{h_W}\right)^2 10^4$$

$$\sigma_{cli} = 32\left(\frac{E_{Xi}}{206000}\right)\left(\frac{t_F}{b_F}\right)^2 10^4$$

where:

h_W : Web height of built-up section, in mm

t_W : Web thickness of built-up section, in mm

b_F : Face plate width of built-up section, in mm

t_F : Face plate thickness of built-up section, in mm

E_{Xi} : Tensile modulus of the basic elements (web and flange), in N/mm^2

3.1.6 Scantling criteria

Three main scantling criteria are to be checked in each basic element of the pillar, regarding:

- maximum stress in each layer
- combined stress in each layer
- local buckling.

In addition, the global buckling of the pillar is to be checked as defined in item d)

a) Maximum stress in each layer:

The maximum stresses in each layer of the elements of the pillar induced by axial load are to satisfy the following criteria:

$\sigma_i \leq \sigma_{br} / SF$

where:

σ_i : Local stresses in individual layers of each element of the pillar as defined in [3.1.3]

σ_{br} : Theoretical breaking stresses of layers as defined in Sec 5

SF : Minimum rule safety factor as defined in Sec 2, [1.3.2].

b) Combined stress in each layer

The combined criterion SF_{CS} is to be in compliance with the equation defined in Sec 2, [1.3.3].

c) Local buckling:

The local buckling of basic element of the pillar is to satisfy the following criteria:

$\sigma_{Ai} \leq \sigma_{cli} / SF_{lBuck}$

where:

σ_{Ai} : Compression stress, in N/mm^2 as defined in [3.1.2]

σ_{cli} : Critical local buckling stresses as defined in [3.1.5]

SF_{lBuck} : Minimum local buckling rule safety factor for pillars defined as defined in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2])

d) Global buckling:

$\sigma_A \leq \sigma_{cg} / SF_{gBuck}$

σ_A : Global stress, in N/mm^2 as defined in [3.1.1]

σ_{cg} : Critical global column buckling stress as defined in [3.1.4]

SF_{Bg} : Minimum column buckling rule safety factor for pillars as defined in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

3.2 Pillar scantling under compressive force and bending moment

3.2.1 Pillar loaded by compression axial load and bending moments are to be checked according to [3.1], taking into account a global strain ε_{AB}, in %, in the basic element of the pillar equal to:

$$\varepsilon_{AB} = \varepsilon_A + \varepsilon_B$$

where:

ε_A : Global strain, in %, in the pillar in its longitudinal axis induced by axial compression load calculated as defined in [3.1.1]

ε_B : Global strain, in %, in the pillar in its longitudinal axis induced by bending moment, to be taken equal to:

$$\varepsilon_B = \frac{M \cdot d_i}{[EI]} \cdot 10^8$$

where:

M : Greater value of the bending moment, in kN·m, applied to the upper end or lower end of the pillar

[EI] : Global bending rigidity of the pillar, in N.mm^2, as defined in Article [2]

d_i : Distance, in mm, between the neutral axis of the basic element considered and the main axis of the pillar

Note 1: Attention is to be paid to the sign of the bending moment M which conditions the type of stresses (tensile or compression) in the basic elements of the pillar.

3.3 Pillars in tanks

3.3.1 Where pillars are submitted to tensile stress due to internal pressure in tank, brackets or equivalent arrangements are to be provided in way of the connection elements between the pillar and the supported structure of the tank.

Pillars in tanks are not to be of hollow profile type.

4 Vertical bulkheads acting as pillar

4.1 General

4.1.1 When a vertical bulkhead stiffener is fitted in line with the deck primary supporting member transferring the loads from the deck to the bulkhead (as a pillar), this vertical stiffener is to be calculated as defined in [3.1] and [3.2] when applicable, taking into account an associated plating of a width equal to 30 times the bulkhead plating thickness.

Section 9 Plate and Stiffener Analysis for Plywood Structure

Symbols

E_1 : Young modulus along the longitudinal axis of the wood grain (in L direction), in N/mm² (see Fig 1)
E_2 : Young modulus in the tangential axis of the wood grain (in T direction), in N/mm² (see Fig 1)
G_{12} : Shear modulus in plan LT of the wood, in N/mm²
G_{13} : Shear modulus in plan LR of the wood, in N/mm²
G_{23} : Shear modulus in plan RT of the wood, in N/mm²
ℓ : Span, in m, of the ordinary or primary considered stiffeners.
ν_{12} : Poisson's coefficient
ν_{21} : Poisson's coefficient
σ_1 tensile: Maximum breaking tensile stress in the longitudinal axis of the wood grain, in N/mm² (see Fig 1)
σ_1 compression : Maximum breaking compression stress in the longitudinal axis of the wood grain, in N/mm² (see Fig 1)
σ_2 tensile: Maximum breaking tensile stress in the transverse axis of the wood grain, in N/mm² (see Fig 1)
σ_2 compression : Maximum breaking compression stress in the transverse axis of the wood grain, in N/mm² (see Fig 1)
s : Spacing, in m, between the ordinary or primary considered stiffeners
τ_{IL1} : Maximum shear stress parallel to the wood grain, in N/mm²
τ_{IL2} : Maximum shear stress perpendicular to the wood grain, in N/mm²

1 Hull structure scantling criteria

1.1 General

1.1.1 The requirements of the present Section are applicable to ships hull made, totally or partly, of plywood.

As a general rule, plywood structures are checked according to the homogeneous plywood material approach defined in [1.1.2].

When several noticeably different wood species sheets are used in the plywood, or where deemed necessary by the Society, a ply by ply plywood approach as defined in [1.1.3] may be considered.

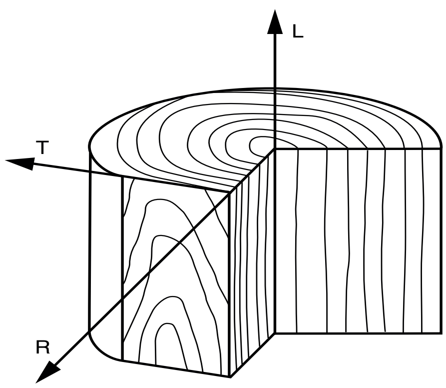
1.1.2 Homogeneous plywood material approach

The scantling formulae defined in the present Section are based on the hypothesis that the plywoods may be considered as homogeneous material, characterized by their main geometrical and mechanical characteristics in the two main directions of the panel.

The main geometrical and mechanical characteristics to be defined by the designer are the:

- panel thickness
- young moduli in the two main directions of the plywood panel
- shear modulus in the plywood plan
- minimum bending breaking stresses in tensile and compression in the two main directions of the panel, and
- minimum shear breaking stress in the plywood plan.

Figure 1 : Local axes of timber



1.1.3 Ply by ply plywood approach

When deemed necessary by the Society, the scantling approach of plywood may be carried out as defined for composite materials (see Sec 6) by a "ply by ply" approach, taking into account the wood species, the number of plies and their thicknesses, and the mechanical characteristics of each ply.

In this case, each ply is to be considered as unidirectional fabrics and the in-plane theoretical layer breaking stresses, as defined in Sec 5, [5.1.1], of the individual layers in their own local axes are to be defined by the plywood manufacturer.

The mechanical characteristics and breaking stresses of wood species, given for information in Tab 1, may be used at the first stage of the structure check. In this case, these hypotheses are to be confirmed by mechanical tests carried out on the complete plywood within the scope of the plywood certification as defined in [2.3].

1.2 Local and global scantling analysis

1.2.1 General

As a general rule, the review of hull structure is to be carried out under a local structure analysis and a global structure analysis.

1.2.2 Local analysis

The local scantling of panels and of ordinary and primary stiffeners is to be reviewed according to the:

- local loads as defined in Sec 2, [2.2]
- rule analysis as defined in Article [3] for plywood panel and in [4] for secondary and primary plywood stiffeners
- minimum rule safety factors as defined in [1.3].

1.2.3 Global analysis

Where deemed necessary by the Society, the global hull girder longitudinal strength and the global strength of catamaran are to be examined under global loads defined in Sec 2, [3].

The overall bending and shear stresses are to determined as defined in Sec 2, [4] and Sec 2, [5].

The minimum rule safety factors are to be as defined in [1.3].

1.3 Minimum rule safety factors

1.3.1 Homogeneous plywood material approach

The minimum rule safety factor SF, taking into account the type of local loads applied to the plywood panel (sea pressure, internal pressure, bottom slamming and side shell impact) is to be at least equal to the minimum values given in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

Table 1 : Mechanical characteristics and breaking stresses of wood species

Characteristics	Timber species name						
	Okoume (Gaboon)	Mahogany	Sipo	Sapelli	Silver birch	Keruing (Gurjan)	Moabi (African pearwood)
Density	0,44	0,54	0,62	0,67	0,68	0,73	0,80
E_1 (in L direction)	9630	11900	13715	14625	15085	16230	17835
E_2 (in T direction)	525	750	950	1060	1115	1260	1480
G_{12}	750	860	940	980	1000	1050	1110
G_{13}	810	1020	1195	1280	1325	1440	1600
G_{23}	185	265	335	375	395	450	525
ν_{12}	0,472	0,467	0,463	0,461	0,460	0,458	0,456
ν_{21}	0,026	0,029	0,032	0,033	0,034	0,036	0,038
σ_1 tensile	62	78	91	102	106	115	125
σ_1 compression	36	46	53	50	56	65	70
σ_2 tensile	2	3	4	4	4	5	6
σ_2 compression	6	9	11	12	13	15	17
$\tau_{IL1} = \tau_{23}$	6.5	8	9	10	10	11	12
$\tau_{IL2} = \tau_{13} = \tau_{12}$	4	6	8	8	8	10	12
Note 1: The values given in this Table are for general guidance only.							

1.3.2 Ply by ply plywood approach

The minimum rule safety factor is defined in relation to the partial safety factors C_R, C_i and C_V.

The minimum rule safety factor SF in each ply, equal to the ratio between the breaking stresses of each ply defined by the manufacturer and/or deduced from Tab 1 and the actual main stresses calculated as defined in Sec 6, [5] to is to be in compliance with:

$SF \geq C_R \cdot C_i \cdot C_V$

where:

C_R : Rule partial safety factor taking into account the type and direction of the main stresses applied to the fibres of the ply

C_I : Rule partial safety factor taking into account the type of loads

C_V : Rule partial safety factor taking into account the ageing effect on the plywood.

These partial safety factors are to be taken at least equal to the minimum values given in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

1.3.3 Buckling analysis

The minimum rule safety factor SF_B in the plywood panel, equal to the ratio between the critical buckling stresses as defined in Sec 6, [4.2] for panel and Sec 7, [3.2.2] for stiffeners, and the actual main stresses induced by global loads is to be at least equal to the minimum values given in the Rules for the classification of ships (see Sec 1, [1.1.2]).

2 Material

2.1 Timber species

2.1.1 Timber species considered in the present Section and used in layers to form a plywood are:

- Okoume (or Gaboon)
- African mahogany
- Sipo
- Sapelli
- Silver birch
- Gurjan (or Keruing), or
- African pearwood (Moabi).

The main elastic and mechanical properties of these timber species are given, for information only, in Tab 1.

Note 1: Other timber species may be considered if the main elastic and mechanical properties listed in the first column of Tab 1 are defined by the plywood manufacturer.

2.2 Plywood

2.2.1 Plywoods used for hull construction are to be of a marine type.

The adhesives used for plies bonding are to be of one of the following types:

- phenolic resin, or
- melamine-formaldehyde resin.

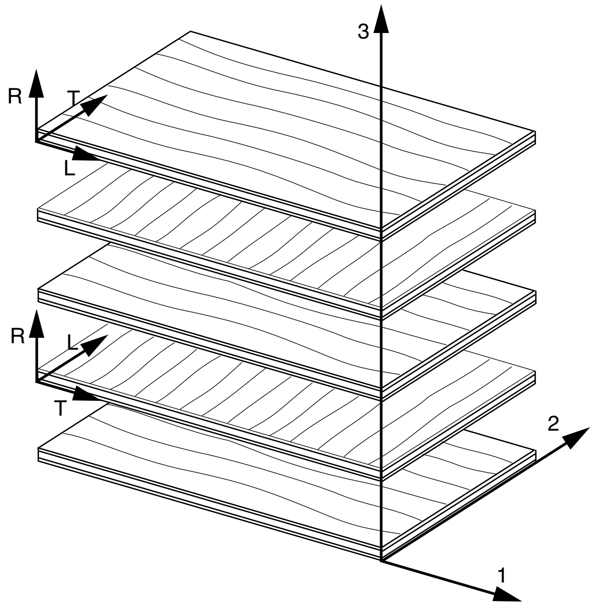
The plywood bonding qualities are to be of Class 3, as defined in standard EN-314.

2.2.2 As a general rule, marine plywoods are to have a minimum density higher than 500 kg/m³ at 12% moisture content.

Table 2 : Relation between plywood thickness and number of plies

Thickness, in mm	Number of plies	Thickness, in mm	Number of plies
3	3	15	9
4	3	18	11
5	3	19	11
6	5	21	15
8	5	22	13
9	7	25	13
10	7	30	15
12	9	35	15
Thickness of each ply is to be defined by the manufacturer.			

Figure 2 : Local and global axes of plywood



2.2.3 Plywood is composed of thin sheets, arranged in layers with the grain direction of adjacent plies at right angles (0°/90°), to form a panel.

Plywood considered in the present Section has always an odd number of layers, obtained from a peeling process.

The strength and elastic properties of plywood are dependent not only on the strength of timber species, but also on the number of plies and their relative thickness.

As a general rule, the number of layers in relation to the plywood thickness is as defined in Tab 2.

The local axes of each ply in relation to the timber grain and the global axes of the plywood are shown on Fig 2.

2.3 Plywood certification

2.3.1 Plywood panels used for hull construction are to be certified according to standard BS 1088 (or equivalent). The technical data sheets are to be submitted by the manufacturer, specifying:

- the manufacturer's name and country
- the name of the timber species
- the reference of the standard used for the certification
- the panel thickness, the number of plies and their thickness
- the main mechanical characteristics of the panel in its two main directions (young moduli, minimum bending breaking stresses and in-plane shear modulus).

Additional mechanical tests may be required by the Society, when deemed necessary, in order to confirm and/or complete the main mechanical values given in the manufacturer's technical data sheets.

2.3.2 Construction mark

As a general rule, a certification of plywood based on BS 1088 and EN-314, combined with possible additional mechanical tests requested by the Society, may be considered as sufficient, within the scope of the classification and/or certification, for the assignment of construction mark .

3 Plywood panel scantling

3.1 Plywood under local loads

3.1.1 Homogeneous plywood panel approach

a) General case:

As a rule, the thickness of plywood panel sustaining lateral pressure is to be not less than the value obtained, in mm, from the following formula:

$$t = 22,4 \cdot \mu \cdot s \cdot \sqrt{\frac{p}{\sigma_{br}/SF}}$$

where:

p : Local pressure (wave loads, internal loads, bottom slamming pressure for high speed ship with planning hull), in kN/m^2, as defined in Sec 2, [2.2] μ : Aspect ratio coefficient of the elementary plate panel, equal to:

$$\mu = 1,21\sqrt{1+0,33\cdot\left(\frac{s}{\ell}\right)^2}-0,69\frac{s}{\ell}\leq 1$$

σ_{br} : Minimum bending breaking stress, in N/mm², given by the plywood manufacturer in the same direction as the direction where s is measured.

When the lay direction of plywood is unknown, the minimum bending breaking stress to be taken into account is the lesser value obtained from the two directions of the plywood

SF : Safety factor defined [1.3.1].

b) Panel of side shell under impact pressure:

As a rule, the thickness of plywood side shell panel and for multihull on platform bottom, subjected to side shell impact pressure is to be not less than the value obtained, in mm, from the following formula:

$$t = 22,4\cdot C_f\cdot\mu\cdot s\cdot\sqrt{\frac{p}{\sigma_{br}/SF}}$$

where:

C_f : Coefficient equal to:

$$C_f = 1 \quad \text{if } \frac{\ell}{0,6}\leq 1+s$$

$$C_f = (1+s)^{-1/2} \quad \text{if } \frac{\ell}{0,6} > 1+s$$

P : Pressure, in KN/m², to be taken equal to: $P = C_p\ P_{ssmin}$

p_{ssmin} : Impact pressure on side shell and, for multihull, on platform bottom, in kN/m², as defined in Sec 2, [2.2]

C_p : Pressure coefficient equal to: $C_p = -0,98s^2 + 0,3s + 0,95 \geq 0,8$

3.1.2 Ply by ply plywood approach

When a ply by ply plywood approach is carried out as specified in [1.1.3], the rule scantling is to be checked taking into account:

- the local loads as defined in Sec 2, [2.2]
- the rule analysis as defined in Sec 6, [5], considering the plywood panel as a monolithic panel
- the rule safety factor SF defined in [1.3.2].

3.2 Plywood under global loads

3.2.1 Plywood panel submitted to global loads as specified in [1.2.3] are to be checked under buckling. The compression and shear stresses applied to the panel are to be defined according to Sec 2.

The compression and shear critical buckling stresses may be determined by the same approach as the one defined for monolithic laminate in Sec 6, [4.2].

The rule safety factor SF_B is to be as defined in [1.3.3].

3.3 Plywood under global and local loads

3.3.1 Application

When deemed necessary by the Society, plywood panel may be checked taking into account lateral pressure combined with global loads.

In this case, the plywood panel is to be checked with a ply by ply approach according to the methodology defined in Sec 6, [7].

3.4 Plywood panel combined with composite laminates

3.4.1 Plywood panels laminated with composite materials are to be examined as defined in Sec 6.

In this case, the plywood panel may be considered:

- as an elementary layer such as a woven roving having a thickness equal to the total plywood thickness, or
- as defined in [1.1.3].

4 Secondary and primary stiffener analysis and scantling approach

4.1 Plywood stiffener under local loads

4.1.1 Stiffener parameters

The neutral axis V and the rigidity [EI] of a stiffener are to be calculated according to Sec 7, [2.2].

In the formulae, the values of the modulus E_{Xi} of each basic element (flange, web and associated panel) in the longitudinal direction of the stiffener are to be given by the plywood supplier.

When the values of E_{Xi} for the plywood basic elements are not available, they may be estimated by the following formula:

$$E_{Xi} = \frac{\sum E_i \cdot e \cdot b_i}{\sum e \cdot b_i}$$

where, for each ply of the plywood:

e_i : Thickness, in mm, of each ply of the basic elements (flange, web or associated plating)

b_i : Breath, in mm, of each ply of the basic elements (flange, web or associated plating)

E_i : Modulus of the wood species of each ply of the basic element (flange, web or associated plating), in N/mm², in relation to the longitudinal axis of the stiffener.

4.1.2 Bending moment and shear force

The bending moment, in kN·m, and the shear force, in kN, under local loads as defined in Sec 2, [2.2] are to be calculated according to Sec 7, [4].

4.1.3 Stiffener scantling check

- The bending strains ε_{xi}, in %, in the attached plywood panel and in the flange are to be calculated according to Sec 7, [3.1.1] a).
- The bending stresses σ, in N/mm²,in the attached plywood panel and in the flange, may be determined as follows:

  $$\sigma = \frac{E_{Xi} \cdot \varepsilon_{xi}}{100}$$

  where:

  E_{Xi} : Longitudinal plywood modulus, in N/mm², of the attached plywood panel and of the flange.

  The bending stress is to fulfil the following condition:

  $\sigma \le \sigma_{br} / SF$

  where:

  σ_{br} : Minimum bending breaking stress of the plywood material, in N/mm², given by the supplier and/or deduced from the mechanical tests

  SF : Safety factor defined in [1.3.1].

- The shear stress τ in the web, in N/mm², may be obtained from the following formula:

  $\tau = T / S$

  where:

  T : Shear force, in N, under local loads as defined in Sec 2, [2.2] calculated according to Sec 7, [4]

  S : Web cross-section, in mm².

  The shear stress is to fulfil the following condition:

  $\tau \le \tau_{br} / SF$

  where:

  τ_{br} : Minimum in-plane shear breaking stress of the material, in N/mm², given by the supplier and/or deduced from the mechanical tests.

  When no value is available, τ_{br} may be taken equal to the values given in Tab 1 (row τ // grain).

  SF : Safety factor defined in [1.3.1].

4.2 Plywood stiffener under global loads

4.2.1 Plywood stiffener submitted to global loads as specified in [1.2.3] are to be checked under buckling. The compression and shear stresses applied to the stiffener are to be defined according to Sec 2.

The compression and shear critical buckling stresses may be determined by the same approach as the one defined in Sec 7, [3.2.2].

The rule safety factor SF_B is to be as defined in [1.3.3].

4.3 Plywood stiffener under global and local loads

4.3.1 Application

When deemed necessary by the Society, plywood stiffener may be checked taking into account lateral pressure combined with global loads.

In this case, the plywood stiffener is to be checked according to the methodology defined in Sec 7, [6].

4.4 Plywood stiffener arrangement

4.4.1 Stiffener connection with attached plating

As a rule, the bonded joint between the stiffener and the attached plating is to be checked according to Sec 7, [11.2].

4.4.2 Plywood stiffener combined with composite laminate

Plywood stiffeners laminated with composite materials are to be examined as defined in Sec 7.

In this case, the plywood basic elements of the stiffener may be considered:

- as an elementary layer such as a woven roving having a thickness equal to the total plywood thickness, or
- as defined in [1.1.3].

5 Working process and material

5.1 General

5.1.1 Workshop requirements, construction and mechanical tests of plywood are to comply with Sec 12, as applicable.

5.2 Structural adhesives

5.2.1 The global approach of structural adhesives for plywood hull construction is the one defined in Sec 4, [5].

Section 10 Plate and Stiffener Analysis for High Density Polyethylene (HDPE) Structure

Symbols

λ : Ageing effect coefficient taken equal to: $\lambda = 1,05$

μ : Aspect ratio coefficient of the elementary plate panel, equal to:

$$\mu = 1,21\sqrt{1 + 0,33\left(\frac{s}{\ell}\right)^2} - 0,69\frac{s}{\ell} \le 1$$

where:

ℓ : Length, in m, of the longer side of the plate panel

s : Length, in m, of the shorter side of the plate panel

m : End stiffener condition coefficient, as defined in Sec 7, [4.1.2] a)

R : Tensile stress at yield of the HDPE, in MPa, as defined in [2.2].

1 Hull structure scantling criteria

1.1 General

1.1.1 The requirements of the present Section are applicable to ships hull made, totally or partly, of high density polyethylene (HDPE) for building based on HDPE sheets.

Ships hulls made with HDPE by rotational moulding process are not covered by the present Rule Note.

1.1.2 General material approach

The scantling formulae defined in the present Section are based on the yield characteristics of the HDPE (stresses and moduli).

The main mechanical characteristics at yield to be defined by the HDPE supplier are the:

- Young modulus
- minimum tensile stress and elongation
- minimum shear stress
- long term service temperature.

The minimum mechanical characteristics of HDPE are given in Tab 1 for information only.

Particular attention is to be taken to avoid the use of HDPE where temperatures may be higher than long term service temperature.

1.2 Hull structure scantling analysis

1.2.1 Local analysis

The review of hull structure is to be carried out under a local structure analysis according to the:

a) Local loads as defined in Sec 2, [2.2.1] taking into account the local load point location defined as follow:
   - for sea pressures and local internal pressures on:
     - panels: at the lower edge of the panel
     - longitudinal stiffeners: at mid-span of the stiffeners
     - transverse stiffeners: at the lower point (p_{slower}) and at the upper point (p_{supper}) of the stiffeners.
   - for dynamic sea pressures on:
     - panels: at the middle of the panels
     - longitudinal and transverse stiffeners: at mid-span of the stiffeners.

b) Rule analysis as defined in [3] for hull panel and secondary and primary stiffeners permissible stresses as defined in [1.3.2].

1.2.2 Global analysis

For ship having a length at the waterline greater than 15 m and a planing hull shape (able to sail in planing mode resulting from hydrodynamic lift), the global hull girder longitudinal strength is to be, as a rule, considered under buckling according to [3.3] due to the small value of the Young modulus of the HDPE.

Note 1: When deemed necessary by the Society, additional global hull girder longitudinal strength verification may be required on a case by case basis.

1.3 Permissible stresses and buckling safety factor

1.3.1 General

The scantling formula defined in the present Section are based on permissible stresses as defined in [1.3.2].

These permissible stresses consider a 20% decrease of the HDPE parent material's mechanical characteristics induced by welding in heat affected zone.

1.3.2 Permissible stresses under local loads

a) General:

The permissible stresses for the structure check are based on the value of the tensile stress at yield R of the HDPE, in MPa, as defined in [2.2], in relation to the type of loads.

b) Plating and secondary stiffeners:

The permissible local stresses for the check of plating and secondary stiffeners submitted to local loads, are defined in Sec 1, [1.1.2] b).

c) Primary stiffeners:

The check of primary stiffeners submitted to local loads is to be carried out taking into account the following permissible stresses:

- for analysis through an isolated beam calculation: σ_{locam} and τ_{locam}
- for analysis through a two or three-dimensional structure beam model: σ_{vmam}

where:

σ_{locam} , τ_{locam} :Permissible local stresses, in N/mm^2, defined in Sec 1, [1.1.2] b),

σ_{vmam} : Permissible local Von Mises equivalent stresses, in N/mm^2, defined in Sec 1, [1.1.2] b)

1.3.3 Buckling safety factor

When the global hull girder strength is examined as required in [1.2.2], the buckling safety factor for plating, is to be as defined in Sec 1, [1.1.2], b).

2 Material

2.1 General

2.1.1 HDPE is a thermoplastic made up of long-chain of molecules (polymer) consisting of a series of small repeating molecular units (monomers).
HDPE is characterized by a good impact resistance, light weight and very low moisture absorption.

2.2 Mechanical characteristics

2.2.1 Taking into account the non-linearity of the HDPE behaviour as shown on Fig 1, the main mechanical characteristics to be considered in the present Section are to be defined by the manufacturer and/or by mechanical tests at the yield limit of the material.

2.2.2 The minimum mechanical characteristics of HDPE at the yield limit are given in Tab 1, for information only.

Figure 1 : Stress / elongation curve

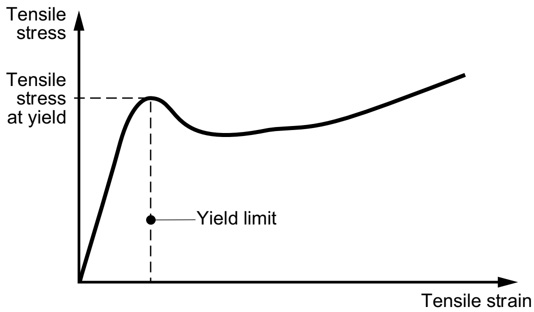


Table 1 : Minimum mechanical characteristics of HDPE

Mechanical properties	Value	Mechanical properties	Values
Density	0,95	Tensile elongation at yield (%)	13
Young modulus at yield (MPa)	950	Shear stress at yield (MPa)	14
Shear modulus at yield (MPa)	300	Poisson's coefficient	0,45
Tensile stress at yield (MPa)	24	Long term service temperature (°C)	80

3 HDPE structure scantling

3.1 Panel scantling under local loads

3.1.1 General case

As a rule, the thickness of plating subjected to lateral pressure (sea or internal pressure and bottom slamming) is to be not less than the value obtained, in mm, from the following formula:

$$t = 22,4\lambda\mu s\sqrt{\frac{p}{\sigma_{locam}}}$$

where:

s : Length, in m, of the shorter side of the plate panel

p :
- local sea pressures or internal pressures, in kN/m², as defined in Sec 1, [1.1.2] b)
- bottom slamming pressure for planing hull, p_{sl}, in kN/m², as defined in Sec 1, [1.1.2] b) calculated taking into account the minimum value of K_{2min} equal to 0,5

σ_{locam} : Local permissible bending stress, in N/mm², as defined in [1.3], in relation to the type of load

3.1.2 Panel scantling of side shell under impact pressure

As a rule, the thickness of side shell plating subjected to impact pressure is to be not less than the value obtained, in mm, from the following formulae:

- if s ≤ 0,6 m

$$t = 17,3\sqrt{\frac{1}{\ell_{ssi}}}\lambda n_p \mu s\sqrt{\frac{p}{\sigma_{locam}}}$$

- if s > 0,6 m

$$t = 13,4\sqrt{\frac{1,5s^2 - 0,18}{\ell_{ssi}s}}\lambda n_p \mu\sqrt{\frac{p}{\sigma_{locam}}}$$

where:

s : Length, in m, of the shorter side of the plate panel

ℓ_{ssi} : Length, in m, equal to: $\ell_{ssi} = 0,6\ (1 + s) \le \ell$

p : Pressure, in kN/m², to be taken equal to: $p = C_p\ P_{ssmin}$

P_{ssmin} : Impact pressure on side shell, in kN/m², as defined in Sec 1, [1.1.2] b)

C_p : Pressure coefficient equal to: $C_p = -0,98\ s^2 + 0,3\ s + 0,95 \ge 0,8$

n_p : Coefficient to be taken equal to: $n_p = 0,80$

σ_{locam} : Local permissible bending stress, in N/mm², as defined in [1.3]

3.1.3 Minimum rule thickness

As a rule, the thicknesses, in mm, of plates calculated according to the present Section are not to be less than 10 mm.

3.2 Secondary and primary stiffeners scantling under local loads

3.2.1 General

The scantling of secondary and primary stiffener analysis is to be carried out taking into account general requirements defined in Sec 7, [4.1.1] and Sec 7, [4.1.2].

3.2.2 General case

As a rule, the section modulus Z, in cm³, and the shear area A_{sh}, in cm², of the secondary and primary stiffeners subjected to lateral local pressures and bottom slamming are to be not less than the values obtained from the following formulae:

a) for horizontal stiffeners (longitudinal or transverse):

$$Z = 1000\lambda\frac{ps\ell^2}{m\sigma_{locam}}$$

$$A_{sh} = 5\lambda\frac{ps\ell}{\tau_{locam}}$$

where:

s : Spacing of the stiffeners, in m

ℓ : Span, in m, of the stiffener under consideration as defined in Sec 7, [4.1.2] b)

p :
- local sea pressures or internal pressures, in kN/m², as defined in Sec 1, [1.1.2] b)
- bottom slamming pressure for planing hull, p_{sl}, in kN/m², as defined in Sec 1, [1.1.2] b)

σ_{locam} : Local permissible bending stress, in N/mm², as defined in [1.3], in relation to the type of load

τ_{locam} : Local permissible shear stress, in N/mm², as defined in [1.3], in relation to the type of load

b) for vertical transverse stiffeners:

$$Z = 1000\lambda \frac{p_1 s \ell^2}{m_b \sigma_{locam}}$$

$$A_{sh} = 10\lambda \frac{p_2 s \ell}{m_s \tau_{locam}}$$

where:

s : Spacing of the stiffeners, in m

ℓ : Span, in m, of the stiffener under consideration as defined in Sec 7, [4.1.2] b)

p_1, p_2 : Equivalent pressure, in kN/m², as defined in Tab 2

m_b, m_s : End stiffener condition coefficients defined in Tab 2.

3.2.3 Secondary stiffener scantling under side shell impact

As a rule, the section modulus Z, in cm³, and the shear area A_{sh}, in cm², of the horizontal and vertical secondary stiffeners sustaining lateral side shell impacts are to be not less than the values obtained from the following formulae:

$$Z = 1000\lambda C_f \frac{P s \ell^2}{m \sigma_{locam}}$$

$$A_{sh} = 5\lambda C_t \frac{P s \ell}{\tau_{locam}}$$

where:

s : Spacing of the stiffeners, in m, not to be taken greater than 0,6 m for the calculation of Z and A_{sh}

ℓ : Span, in m, of the stiffener under consideration as defined in Sec 7, [4.1.2] b)

P : Pressure, in kN/m², to be taken equal to: $P = 0{,}85.C_p.P_{ssmin}$

C_p : Pressure coefficient equal to: $C_p = -0{,}98s^2 + 0{,}3s + 0{,}95 \geq 0{,}8$

P_{ssmin} : Impact pressure on side shell in kN/m², as defined in Sec 1, [1.1.2] b)

C_f, C_t : Reduction coefficients equal to:

$C_f = 0{,}3\ (3\ \ell^2 - 0{,}36) / \ell^3$ with $\ell \geq 0{,}6$ m

$C_t = 0{,}6 / \ell$ without being taken greater than 1.

3.2.4 Minimum secondary stiffener section modulus

As a rule, the minimum section modulus of hull and deck secondary stiffeners is not to be less than 15 cm³.

3.3 Buckling check under global loads

3.3.1 General

When required according to [1.2.2], the global strength analysis is to be carried out taking into account the:

- overall bending moment and shear force in planing hull mode (due to still water plus wave induced loads plus impact loads) as defined in the Society Rules (see Sec 1, [1.1.2] b)
- buckling safety factor as defined in [1.3.3].

3.3.2 Transverse section strength characteristics

The calculation of the hull girder strength characteristics is to be carried out as defined in the Society Rules (see Sec 1, [1.1.2] b) taking into account all the longitudinal continuous structural elements of the hull.

3.3.3 Buckling check

It is to be checked, for deck plating and upper side shell plating contributing to the global hull girder strength, that the actual normal stresses and shear stresses calculated taking into account the overall bending moment and shear force in planing hull mode and the transverse section strength characteristics of the hull fulfil the buckling criteria defined in [1.3.3].

Table 2 : Equivalent pressures

End stiffener condition	P_1	m_b	P_2	m_s
Both ends fixed	$2\ p_{Supper} + 3\ p_{Slower}$	60	$3\ p_{Supper} + 7\ p_{Slower}$	20
Lower end fixed, upper end supported	$7\ p_{Supper} + 8\ p_{Slower}$	120	$9\ p_{Supper} + 16\ p_{Slower}$	40
Both ends supported	$p_{Supper} + p_{Slower}$	16	$p_{Supper} + 2\ p_{Slower}$	6

Note 1:

p_{slower}, p_{supper}, : Sea pressure or internal pressure calculated at lower end of the stiffener and at upper end of the stiffener respectively, in KN/m², as defined in the applicable Society Rules defined in Sec 1, [1.1.2] b).

4 Weld scantling

4.1 General

4.1.1 Weld booklet

A weld booklet, including the weld scantling such as throat thickness and design of joint, is to be submitted to the Society for examination.

The weld booklet is not required if the structure drawings submitted to the Society contain the necessary relevant data defining the weld scantling.

4.1.2 Butt welds

As a rule, butt welding is to be used for plate and stiffener butts and is mandatory for heavily stressed butts such as those of the bottom, keel, side shell, sheerstrake and strength deck plating, and bulkheads (in particular bulkheads located in areas where vibrations occur).

As a rule, the structural butt joints are to be full penetration welds, performed from both sides.

4.1.3 Fillet welds

As a rule, double continuous fillet welds are to be provided. The total throat thickness weld is not to be less than the thinner plate of the assembly.

Other throat thickness may be considered on a case by case basis by the Society.

5 Working process and survey at works

5.1 General

5.1.1 Survey at works

The general principles of surveys required by the Society during ship hull construction within the scope of the classification and/or certification of ships built in unit production or in mass production are to be based on the principles defined in Sec 12, [5] to Sec 12, [7].

5.1.2 Homologation and certification of material

The main purpose of the homologation of material is defined in Sec 12, [2.1.1].

Material used for hull construction are to be certified according to recognized standards. The technical data sheets, specifying the mechanical properties listed in Tab 1 are to be submitted by the manufacturer.

Additional mechanical tests such as measurement of density (according to ISO 1183 or equivalent), tensile properties (according to IS0 527 or equivalent) may be required by the Society.

5.2 Welding

5.2.1 Welding booklet

A welding booklet including the welding procedures, operations, inspections and the modifications and repair during construction is to be submitted to the Surveyor for examination.

This welding booklet is to include:

- description of the welding process
- mechanical characteristics of welding rod
- cleaning process of welded areas before welding
- pre-heating of weld starting point and welding heating temperature
- means to avoid distortion
- for each type of joint, the preparations and the various welding parameters
- welded joints inspection program
- welding defects acceptance criteria and repair procedures

5.2.2 Welding test

As a rule, mechanical test results, representative of the hull construction, are to be submitted to the Society for examination.

These tests are to be carried out according to recognized standards (for example ISO EN 12814 for bending and tensile tests) or equivalent.

The breaking stress of the welded specimens are to be at least equal to 80% of the breaking stress of the unwelded material.

5.2.3 Welder qualification and equipment

As a rule, welder qualification and equipment are to be carried out according to a recognized standard ISO EN 13067 or equivalent).

Section 11 Composite Shaft Line

Symbols

D : External diameter, in mm, of the composite tube
d : Internal diameter, in mm, of the composite tube
E_X, E_y : Tensile modulus of the laminate of the composite shaft, in N/mm², in the two main directions X and Y of the shaft as defined in Sec 6, [2.2.1]
G_{XY} : In-plane shear modulus of the laminate of the composite shaft, in N/mm², as defined in Sec 6, [2.2.1]
ν_x, ν_y : Poisson's ratio of the laminate of the composite shaft as defined in Sec 6, [2.2.1]
L : Length, in mm, of the composite tube
I_{tr} : Torsion inertia of the composite tube, in mm⁴
I_b : Bending inertia of the composite tube, in mm⁴
P_W : Weight per meter, in kg/m, of the composite tube equal to: $P_W = 2.\pi . r . W . 10^{-3}$
R : External radius, in mm, of the composite tube to be taken equal to: R = D/2
r : Mean radius, in mm, of the composite tube to be taken equal to: r = (d + t)/2
S : Cross section area of the composite tube, in mm²
t : Thickness, in mm, of the composite tube
W_{tr} : Torsion modulus of the composite tube, in mm³, calculated at mean radius r
W_b : Bending modulus of the composite tube, in mm³, calculated at mean radius r
W : Laminate weight, in kg/m², as defined in Sec 6, [2.1.5].

1 General

1.1 Application

1.1.1 This Section applies for the scantling check of hollow tubular composite shaft lines for main propulsion having traditional design features. Other shafts will be given special consideration by the Society.

The applicable requirements of the Society Rules for the Classification of Steel Ships, NR467, Pt C, Ch 1, Sec 7, or for the Classification of Inland Navigation Vessels, NR217, Pt C, Ch 1, Sec 7, are to be considered for the installation and arrangement, alignment and scantling of specific components transmitting power for main propulsion not covered by the present Section.

The general arrangement in relation to fire is not covered by the present Section and is to be examined on a case by case basis.

1.2 Operational conditions

1.2.1 Normal operational conditions considered for the shaft line scantling check are:

- temperature within the range +5° C to +55°C
- relative humidity within the range 0% to 96%.

Other operational conditions may be considered by the Society. In this case, the operational conditions are to be specified by the manufacturer and may be taken into account during the mechanical tests defined in Article [2].

1.3 Materials

1.3.1 Raw materials

Mechanical characteristics and certification of raw materials are defined in Sec 4 and App 1.

The present section is mainly dedicated to shaft line built with raw materials defined in Sec 4. Other type of materials may be considered as defined in Sec 4, [1.2.6]. In this case, information in relation with fatigue strength are to be specified by the manufacturer (see Article [7]).

Adhesives for bonding connection are to be selected with due regard to the normal operational condition. Test results and technical informations are to be submitted to the Society, specially for:

- shear strength and typical shear stress-strain curves
- corrosion resistance when connections with steel pins and bolts are provided.

Attention is to be paid on glass transition temperature of resins and adhesives in relation with the operational conditions.

1.3.2 Laminate process

As a rule, the requirements regarding the shaft line laminate process are to be as defined in Sec 12.

1.4 Documents to be submitted

1.4.1 The drawings and documents to be submitted for shaft line structure review are:

- shafting arrangement showing the entire shafting, specifying the maximum continuous power of the machinery, the speed of rotation of the shaft corresponding to the maximum continuous power, and the nominal torque
- laminate composition for nominal and reinforced sections of the composite shaft (see Sec 1, [4.2.1]
- technical data sheets of raw materials of composite shaft line (see Sec 1, [4.2.2])
- laminating process of the composite shaft and its connections to the other parts of the shaft line
- manufacturer design analysis for information (when fatigue strength is required, design calculation and required number of load cycles are to be submitted)
- mechanical test results (see Article [2]).

2 Test and survey at works

2.1 General

2.1.1 Tests and survey at works are to be defined on a case by case basis and are to be carried out based on the general process defined in:

- Sec 12, [6] for composite shaft unit production
- Sec 12, [7] for composite shaft series production.

As a rule, the composite shaft line is to be tested after completion with ends coupling parts under static torsional loads to be taken at least equal to 1,3 the nominal torque. Instrumentation is to be provided for continuously measuring the torque and the twist between end couplings.

3 Scantling check

3.1 General

3.1.1 As a rule, the scantling check of the shaft line is to be carried out taking into account the present Section and the following loads and hypothesis:

- static loads (see Article [4])
- buckling (see Article [5])
- vibratory loads (see Article [6])
- fatigue (see Article [7]).

3.1.2 Other alternative calculation methods may be considered on a case by case basis.

4 Design check of shaft line under static loads

4.1 Loads

4.1.1 As a rule, the following loads are to be taken into account:

- peak torque
- axial force and secondary bending moments induced by relative movements of the shaft line and hull structure deformation:
  - tensile and compressive axial force induced by axial relative movement
  - bending moment induced by angular relative movement
- hydrodynamic propeller horizontal force as applicable.

Note 1: Bending moments induced by radial relative movement may be overlooked.

4.1.2 Torsional moment induced by peak torque

The peak torsional moment, in KNm, is to be taken at least equal to:

$C_t = 1,3 \, . \, C_n$

where:

C_n : Nominal torque, in KNm, given by the Designer. When this value is not available, C_n may be taken equal to:

$C_n = (60P)/(2\pi n)$

where:

P : Maximum continuous power of the engine, in KW

n : Speed of rotation of the shaft, in revolution per minute, corresponding to power P.

4.1.3 Axial force and secondary bending moment

The axial force and secondary bending moment induced by relative movements of the shaft line and hull structure deformation are to be as follow:

- Tensile and/or compressive axial force induced by axial relative movement, in kN:

  $F_a = 0,2 \cdot \varepsilon_{ax} \cdot E_X \cdot S \cdot 10^{-5}$

  ε_{ax} : Axial misalignment strain, in %, to be given by the Designer and taken equal to:

  $\varepsilon_{ax} = (\text{axial misalignment} / L) \cdot 100$

  When no value is available, ε_{ax} may be taken not less than 0,1%

- Bending moment induced by angular relative movement, in KNm:

$$M_a = \frac{0,2\theta E_X I_b}{L} 10^{-6}$$

where:

θ : Angular misalignment, in rad, to be given by the Designer. When no value is available, θ may be taken equal to 0,025 rad.

4.1.4 Hydrodynamic propeller horizontal force

The horizontal compressive force F_t, in kN, is to be defined by the designer for part of shaft lines submitted to the thrust force, as applicable in relation to the thrust block arrangement and location.

4.2 Strain and stresses in the composite shaft line

4.2.1 General

a) Strain in the laminate shaft line:

The strains, in %, in the laminate shaft line induced by peak torque, bending moments and tensile and/or compressive forces are to be calculated as follow:

$$\gamma_{XY} = \frac{C_t}{W_{tr} G_{XY}} 10^8$$

$$\varepsilon_{xbi} = \frac{M_a}{E_X W_b} 10^8$$

$$\varepsilon_{xi} = \frac{\sum F_i}{E_X S} 10^5$$

where:

C_t : Peak torque, in KNm, as defined in [4.1.2]

M_a : Bending moments induced by angular relative movement, in KNm, as defined in [4.1.3]

F_i : Axial forces, in kN, induced by axial relative movement as defined in [4.1.3]and hydrodynamic propeller horizontal force, as applicable.

b) Stress in the individual layers:

The tensile, compressive and shear local stresses, in N/mm², in the local axis of each layer of the laminates of the shaft line, are to be calculated as defined in Sec 6, [3.2.3], taking into account simultaneously:

- the sum of ε_{xbi} and ε_{xi}, and
- γ_{xy}

defined in [4.2.1] a).

The calculation methodology proposed in Article [9] may be used.

4.2.2 Calculation methodology

A calculation methodology proposed in [9] may be used. Other equivalent calculation approach may be considered.

4.3 Scantling criteria under static loads

4.3.1 The scantling criteria under static loads are based on the analysis of the main stresses and the combined stresses in the individual layers of the laminate shaft line as defined in Sec 2, [1.3], taking into account the following values of the partial safety factors:

a) Main stresses in individual layers: $SF \geq C_V \cdot C_F \cdot C'_R \cdot C_i$

b) Combined stresses: $SF_{CS} \geq C_{CS} \cdot C_V \cdot C_F \cdot C_i$

where:

C_V : Coefficient taking into account the ageing effect of the composites. C_V is generally to be taken equal to 1,1

C_F : Coefficient taking into account the fabrication process and the reproducibility of the fabrication.

- 1,1in case of a prepreg process or filament winding process
- 1,15 in case of infusion and vacuum process

C'_R : Coefficient taking into account the type of stress in the fibres of the reinforcement fabric. C'_R is generally to be taken equal to:

- 4,6 for a tensile or compressive stress parallel to the continuous fibre of the reinforcement fabric
- 2,2 for tensile or compressive stress perpendicular to the continuous fibre of the reinforcement fabric
- 3,5 for a shear stress parallel to the fibre in the elementary layer and for interlaminar shear stress in the laminate

C_{CS} : Coefficient for combined stress, generally to be taken equal to 3,1

C_i : Factor to be taken equal to 0,9.

4.3.2 Lower safety factors than factors defined in [4.3.1] may be considered on a case by case basis when a fatigue analysis calculation according to Article [7] is submitted for examination.

5 Buckling analysis

5.1 General

5.1.1 The shaft line buckling, based on a global laminate shaft line analysis, is to satisfy the following criteria:

$\sigma_x \leq \sigma_{cx} / SF_B$

$\tau_s \leq \tau_{cx} / SF_B$

where:

σ_x : Sum of the compression stresses, in N/mm², induced by compressive forces and bending moments and calculated as follow:

$\sigma_x = (\varepsilon_{xbi} + \varepsilon_{xi}) \cdot E_X \cdot 10^{-2}$

where:

ε_{xbi} , ε_{xi} : Strains, in %, as defined in [4.2.1]

τ_s : Shear stress, in N/mm², induced by peak torque and calculated as follow:

$\tau_s = \gamma_{xy} \cdot G_{xy} \cdot 10^{-2}$

where:

γ_{xy} : Strains, in %, as defined in [4.2.1]

σ_{cx} , τ_{cx} : Critical buckling stresses, in N/mm², of the laminate shaft line as defined in b) and a) respectively

SF_B : Minimum buckling rule safety factor as defined in [5.1.2].

a) Critical compressive buckling stress:

The critical compressive buckling stress, in N/mm², is to be taken equal to:

$$\sigma_{cx} = 0,55 \frac{E_X t}{R\sqrt{3(1-\nu^2)}}$$

where:

ν : Minimum value of the laminate shaft line poisson's ratio ν_x and ν_y

b) Critical shear buckling stress:

The critical shear buckling stress, in N/mm², is to be taken equal:

$$\tau_{cx} = 0,82 E_x^{3/8} \left(\frac{E_y}{1-\nu_x \nu_y}\right)^{5/8} \sqrt{\frac{R}{L}} \left(\frac{t}{R}\right)^{5/4}$$

5.1.2 Scantling criteria under buckling

The scantling criteria of the global laminate shaft line buckling, based on the minimum buckling rule safety factor SF_B, is to fulfil the following condition:

$SF_B \geq C_{Buck} \cdot C_V \cdot C_F \cdot C_i$

where:

C_{Buck} : Buckling coefficient, to be taken equal to 2,15

C_V, C_F : Partial safety factors defined in [4.3.1]

C_i : Factor to be taken equal to 0,9.

6 Design check of shaft vibration

6.1 Critical speeds

6.1.1 General

As a rule, torsional vibration calculations are to be submitted for the following installation:

- propulsion systems with prime movers developing 220 kW or more
- other systems with internal combustion engines developing 110 kW or more and driving auxiliary machinery intended for essential services.

Torsional vibration calculations are to be carried out using a recognised method and are to comply with the requirements of NR467, Pt C, Ch 1, Sec 9 for ships, and NR271, Pt C, Ch 1, Sec 9 for inland navigation vessels, where applicable.

6.1.2 For other installations than those defined in [6.1.1], the following critical bending and torsional vibration speeds, in rpm, of the shaft line may be determined as follow:

a) Bending vibration:

$$V_{cb} = \frac{60\lambda^2}{2\pi}\sqrt{\frac{E_x I_b 10^3}{ML^3}}$$

where:

M : Mass of the composite shaft line, in kg

λ : Coefficients to be taken, for the first 3 natural frequency modes, successively equal to π, 2π and 3π.

b) Torsional vibration:

$$V_{ct} = \frac{60\lambda}{2\pi}\sqrt{\frac{G_{XY} I_{tr} 10^3}{\rho I_p L^2}}$$

where:

ρ : Density of the laminate shaft line, in kg/mm^3

I_p : Inertia, in mm^4, to be taken equal to:

$$I_p = \frac{\pi D^2 (D^2 - d^2)}{16}$$

λ : Coefficients to be taken, for the first 3 natural frequency modes, successively equal to π, 2π and 3π.

Note 1: The critical bending and torsional vibration speeds are determined on the basis of a shaft line simply supported for bending and free for torsional.

6.2 Checking criteria

6.2.1 Where the critical vibration speeds are closed to the shaft line speed in normal operating ranges, limits of restricted speed range are to be provided. As a rule, these limits should be at least 10% more and less than the critical vibration speed.

7 Design check under fatigue

7.1 General

7.1.1 When deemed necessary by the Society, fatigue analysis of the composite tube and its connections with hubs, based on recognised method, is to be submitted for examination, or full scale testing may be required.

As a rule, when actual safety coefficients, calculated as defined in Article [4] for static loads taking into account the peak torque, are greater than the minimum values given in [4.3.1], fatigue analysis is normally not required.

7.2 Fatigue analysis methodology

7.2.1 General

The fatigue analysis is to be based on the S/N curve for a specified R ratio (R ratio is defined as the minimum stress divided by the maximum stress) for the shaft line composite material considered.

The S/N curves obtained for R ratios relevant for the loading cases considered is to be submitted. If the shaft line is submitted to fatigue stresses of other R ratios than the S/N curves, a constant amplitude lifetime calculation method, or diagram, is to be submitted.

The cyclic stresses are mainly the cyclic stresses induced by the vibratory torsional torque. However, cyclic stresses induced by the bending moment due to angular relative movement may be taken into account.

As a rule, only the cyclic stresses induced by normal and continuous operations are to be taken into account. For each considered loading, the mean stress, the amplitude of the vibratory stress and the required number of cycles are to be specified.

7.2.2 Total damage

The total damage ratio D is the sum of each elementary damage ration D_i corresponding to each specific loading cases.

The total damage ratio D may be calculated with the Miner's damage accumulation rule and is to satisfy:

$$D = \sum_i D_i = \sum_i \frac{n_i}{N_{Ri}} \leq \frac{1}{SF}$$

where:

n_i : Required number of cycles for the cyclic loading considered

N_{Ri} : Number of cycles necessary to the failure for cyclic loading considered

SF : Safety factor to be defined on a case by case basis. As a rule, the safety coefficient is to be not less than 2.

7.2.3 Full scale fatigue test

When a full scale fatigue test is carried out, the fatigue test conditions are to be submitted to the Society for examination.

8 Shaft line coupling

8.1 Scantling check of connection

8.1.1 General

The present Article is dedicated to the scantling check of the connection between the shaft line and the hub coupling only. The coupling scantling and arrangement are to be as defined in NR467, Pt C, Ch 1, Sec 7 for ships and NR217, Pt C, Ch 1, Sec 7 for inland navigation vessels.

Note 1: Coupling made in composite materials are to be considered on a case by case basis by the Society. Designer calculation method is to be submitted for examination, and is to take into account design criteria for continuous and transient operating loads (dimensioning for fatigue strength) and for peak operating loads (dimensioning for static loads).

The scantling check of the connection between shaft line and hubs is to be carried out taking into account the static loads induced by the torsional moment due to peak torque as defined in [4.1.2].

When deemed necessary by the Society, especially when bonding connection is not combined with bolting arrangement, fatigue analyses may be required. In these cases, the informations defined in [7.2.1]are to be submitted for examination.

8.1.2 Scantling criteria

a) Shear force in the connection:

The shear force F, in kN, to take into account for the connection scantling check is to be taken equal to:

$$F = \frac{2C_t}{d_i} 10^3$$

where:

C_t : Peak torsional moment, in kNm as defined in [4.1.2]

d_i : Diameter, in mm, of the hub/shaft line joint

b) Connection scantling:

- For bolted connection:

  The shear stress τ_b, in N/mm², in each bolt is to be taken equal to:

  $$\tau_b = \frac{4F}{\pi d_b^2 n_b} 10^3$$

  The contact force N, in N, in the composite tube in way of each bolt is to be taken equal to:

  $$N = \frac{F}{n_b} 10^3$$

  where:

  d_b : Bolt diameter, in mm, of bolt

  n_b : Number of bolts

  t : Thickness, in mm, of the composite tube in way of the bolts

- For bonding connection:

  The shear stress τ_g, in N/mm², is to be taken equal to:

  $$\tau_g = \frac{F}{\pi d_i \ell} 10^3$$

  where:

  d_i : Diameter, in mm, of the hub/shaft line joint

  ℓ : Length, in mm, if the hub/shaft line joint

c) Scantling criteria:

- For bolted connection:

  - The shear stresses τ_b, in N/mm², calculated according to b) are to comply with the following criteria:

    $$\tau_b \leq \frac{0{,}18 R_{mB}}{\sqrt{3}}$$

    where:

    R_{mB} : Value of the minimum tensile strength of coupling bolt, in N/mm²

  - The contact stress σ_i, in N/mm², in each layer of the composite tube in way of each bolt induced by the contact force N calculated according to b) is to be calculated according to Sec 6, [3.2].

    The scantling criteria are to be as defined in [4.3.1] where SF and SF_{CS} may be taken equal to the values given in [4.3.1] reduced to 55%.

- For bonding connection:

  The shear stresses τ_g, in N/mm², calculated according to b) are to comply with the following criteria:

  $\tau_g \leq \tau_{br} / 3{,}6.C_F$

  where:

  τ_{br} : Maximum breaking shear stress as defined in Sec 4, [5.2].

  C_F : Coefficient taking into account the gluing process, and generally taken equal to:

  - 1,4 in case of a vacuum process with rising curing temperature
  - 1,5 in case of vacuum process
  - 1,7 in the other cases.

8.1.3 Tests

The connection is to be tested as specified in [2.1.1].

9 Calculation methodology proposal

9.1 Static loads

9.1.1 General

For hollow tubular composite shaft line, the Society computer software ComposeIT may be used for the scantling check under static loads as defined in [4], according to the methodology defined in the present Article.

As a rule, this approach can be used when the thickness t of the shaft line is less or equal than 0,2 time the mean radius of the shaft line only.

Other scantling checking methodology may be considered by the Society.

9.1.2 Composite shaft line description

The raw materials, individual layers and composite tube laminate data are to be defined in the software as provided in Sec 6.

9.1.3 Composite shaft line loading and scantling check

a) Model loading:

   The composite tube laminate loading may be carried out in the software ComposeIT by input the strains, in %, calculated in [4.2.1] in the laminate as follow:

   - Shear due to peak torque: γ_{XY}
   - Compression due to bending moments and compression force: $-(\varepsilon_{xbi} + \varepsilon_{xi})$

b) Shaft line scantling check:

   The scantling check is to be carried out as defined in [4.3].

Section 12 Hull Construction, Survey, Tank tests and Mechanical Tests and Raw Material Homologation

1 General

1.1 Scope

1.1.1 The purpose of this Section is to specify the requirements regarding hull design assessment, construction, survey, mechanical tests and homologation of raw materials within the scope of the classification and/or certification of ship hulls built in compliance with the applicable Society's Rules.

2 Homologation and certification of raw materials

2.1 General

2.1.1 General

The purpose of the homologation, by the Society, of raw materials is to check the compliance of the characteristics of the materials used for the structure with the requirements of the relevant Rules of the Society.

The homologation of raw materials conditions one of the main requirements allowing the hull construction marks to be granted by the Society within the scope of the classification and/or certification, as defined in the Rules for the classification and/or certification of ships (see Sec 1, [1.1.2] b).

2.1.2 Application

As a general rule, raw materials are to be submitted to:

- for composite materials: an homologation process as defined in App 1
- for plywood materials: a certification process as defined in Sec 9, [2.3]
- for HDPE material: a certification process as defined in Sec 10, [5.1.2].

3 Structure design assessment

3.1 General

3.1.1 The structure drawing examination is to be carried out in accordance with the present Rule Note and the applicable requirements of the Society Rules (see Sec 1, [1.1.2]).

The examination of structure drawings and hull scantlings is based on the results of the laminate mechanical test panels defined in Article [4].

4 Mechanical tests on laminate test panels

4.1 General

4.1.1 Application

Mechanical and physico-chemical tests are to be performed on test panels produced by the shipyard and representative of the construction of the hull.

The results of the mechanical tests are to be compared with the theoretical properties of the hull composite materials determined on the basis of the requirements of the present Rule Note and considered for the structure design assessment.

To be representative of the yard production methods and of the hull structure under classification and/or certification, each test panel is to be:

- manufactured from the same raw materials as the hull
- manufactured by the same methods as the hull and in the same environment, and particularly with the same heat curing cycle, when applicable
- of a composition equivalent to the laminates used for the hull in type and arrangement of layers (see [4.1.2]).

4.1.2 Composition of the test panel laminate

The composition of the laminate test panel is to be representative of the hull construction and is to be defined by the Society.

As a rule, the laminate test panel is to be the same than the hull bottom or the side shell.

However, when the hull laminate is built up by series of identical stacking sequences, the test panel laminate may be limited to a reduce number of identical stacking sequence in order to reduce the breaking forces during the tests. In this case, for sandwich test panel, the first layers between core and skins are to be the same than those provided in the hull.

It can be requested, where reinforcement fabrics are provided with directions different from 0°/90° in the hull, that these fabrics be placed with 0°/90°directions in the sample tests to avoid test panel disruption.

The mechanical tests are to be carried out in the Society's laboratories or in a laboratory recognized by the Society.

4.2 Mechanical type tests

4.2.1 General

Tests comprise destructive mechanical and physico-chemical tests.

The laminate panel dimensions and/or the number of test pieces are defined in Tab 1.

4.2.2 Application

Tests are done on test pieces taken from the panel in two perpendicular directions. The number of test pieces in each direction depends on the reference standard (usually five in each direction for each test).

Each test piece is to be identified with the Surveyor's agreement and is to specify:

- the test piece direction in relation to the main longitudinal and transverse axes of the hull
- the arrangement of the layers.

4.2.3 Type of tests

Tab 1 gives the types of tests to be performed. Standards indicated in the table are given for information. Equivalent recognized standards may be used with the agreement of the Society. In any case, the dimensions of the test pieces are to be as defined in Tab 1.

As a rule, the following tests are to be performed:

a) General case:

- monolithic laminates: tensile test and/or 3-point bending test, measurement of density and percentage of reinforcement in weight
- sandwich laminates: 3-point bending test and, for each skin, tensile test, measurement of density and percentage of reinforcement in weight

Additional or different tests to those defined in Tab 1 may be requested, at the satisfaction of the Society, when it is necessary to characterize particular laminate or laminating process or structural assembly.

Bending tests are carried out with the load applied on the gel-coat side or on the opposite side. The side is to be chosen in agreement with the Society, in such a way that the test piece will break in a way representative of the relevant shell plating.

b) Particular cases:

When deemed necessary by the Society, additional mechanical tests may be required such as:

- Monolithic:

  bending tests with short length of test pieces to determine the main mechanical characteristics in interlaminar shear stress.
- Sandwich:

  4-point bending test to define the shear characteristics of the core and of the bonding between core and skins (see also [4.2.3] c)
- Structural gluing joint:
  - General:

    Mechanical tests are to be carried out for structural gluing joints. The type of tests and the temperature range are to be defined at the satisfaction of the Society.

    The type and preparation of adherent, the application of adhesive and the curing process of test samples are to be representative of the construction process.

    The characteristics of the sample tests (geometry and thickness of the gluing joint, stiffness of the adherents) are to be as much as possible representative of the actual joint to be characterized.
  - Documents to be submitted:

    A test program specifying the considered mechanical tests and the number of specimen to be tested is to be submitted to the Society.

    A technical report including the forces/displacements curves and failure faces is to be submitted to the Society.

c) Special consideration for sandwich tests:

To avoid significant deterioration of strength and stiffness properties of sandwich test samples by collapse with the core crushing beneath the fixed and moving rollers due to local instability of the compressive face sheets, it may be necessary to provide in way of these rollers supports large enough to avoid excessive indentation of the sandwich. As a rule, an aluminium alloy plate, or equivalent, of 35mm width and 15 mm thick may be used.

When collapse by core crushing may occur, shear tests according to ASTM C273 may be carried out instead of bending tests. In this case, 5 tests pieces with a size of 250 mm length by 2xe width are to be provided.

Table 1 : Mechanical type test

Panels	Test types - Standards	Quantity of test pieces	Size of test pieces, in mm**(1)(2)**
Monolithic	Tensile test: ISO 527	• 5 in lengthwise direction of panel • 5 in crosswise direction of panel • 2 test pieces for calibration **(7)**	Length: 400 Width: • 25 where e < 25 • 30 where 25 < e < 30 • 35 where 30 < e < 35, etc.
	3-point bending test: ISO 14125	• 5 in lengthwise direction of panel • 5 in crosswise direction of panel • 2 test pieces for calibration **(7)**	Length: 200 Width: • 25 where e < 25 • 30 where 25 < e < 30 • 35 where 30 < e < 35, etc.
	Measurement of density: ISO 1183 Reinforcement content in weight: ISO 1172**(3)**	4 samples	30 x 30
Sandwich	3-point bending test ISO 14125 **(6)**	• 5 in lengthwise direction of panel • 5 in crosswise direction of panel • 2 test pieces for calibration **(7)**	Length: 1000**(5)** Width: 2 · e
	For both skins: Tensile test: ISO 527, or equivalent **(4)**	• 5 in lengthwise direction of panel • 5 in crosswise direction of panel • 2 test pieces for calibration **(7)**	Length: 400 Width: • 25 where e < 25 • 30 where 25 < e < 30 • 35 where 30 < e < 35, etc.
	For both skins: Measurement of density: ISO 1183 Reinforcement content in weight: ISO 1172**(3)**	4 samples	30 x 30

(1) The Society may request additional tests with other sizes of test pieces.
(2) e : Thickness, in mm, of the piece under test.
(3) For laminate test panels reinforced with carbon and/or para-aramid fibres, the standard ASTMD3171 may be used.
(4) Where both skins of the sandwich panel are fairly similar, tensile and density tests may be confined to one of the two skins.
(5) The distance between the fixed rollers is to be not less than 600 mm (It is recommended to use a value roughly equal to 800 mm).
(6) See [4.2.3] c)
(7) For orthotrope panel, test may be confined to one direction of the panel.

4.2.4 Reports

Selection of the test results to be recorded and of the test reports are to be as defined by the test standard taken into account.

5 Hull construction and shipyard procedures

5.1 Shipyard details and procedures

5.1.1 The following details are to be submitted by the shipyard to the Society:

- design office and production work staff
- production capacity (number of units per year, number of types, sizes)
- total number of hull units already built
- yard lay-out showing area assigned to different material preparation and hull construction operations.

5.1.2 The following procedures are to be submitted by the shipyard to the Society:

- Traceability
  - procedure to ensure traceability of raw materials and equipment covered by the Society's Rules (from the purchase order to the installation or placing on ship)
  - data to ensure traceability of the production means (describing different steps during production, such as inspection or recording)
  - handing of non-conformities (from the reception of materials or equipment to the end of the construction)
  - handling of client complaints and returns to after-sales department.

- Construction
  - identification of laminating site on lay-out plan
  - laminating method (e.g. hand or spray lay-up, pre-pregs, etc.)
  - average time elapsing between applications of layers
  - hygrometry and temperature monitoring (minima and maxima of temperature and hygrometry)
  - location of hygrometer and thermometer in laminating unit.
- Assembly operations
  - types of assembly (e.g. glue-assembly, matting-in connection)
  - physico-chemical preparations of parts for assembly
  - areas of completion of such preparations (where such operations generate large amounts of dust, details of the precautions taken to limit the effects on assembly work or other operations performed nearby, such as gel-coating or laminating, are to be specified)
  - procedure to ensure that the hull is built in accordance with the approved drawings (as defined in [3])
  - builder's inspection process and handling of defects
  - procedure to ensure that the remedial measures concerning the defects and deficiencies noticed by the Surveyor of the Society during the survey are taken into account
  - precautions taken to comply with the requirements of the suppliers and the Society in order not to cause, during installation, structure damages affecting structural strength and watertightness
  - preparation to be made on the hull in anticipation of installation.

5.2 Materials

5.2.1 The following details about raw materials used in the construction (gel coats, laminating and bonding resins, reinforcements, core materials and adhesives) are to be submitted by the shipyard to the Society:

- list of raw materials used (gel-coats, resins, catalysts/ accelerators and/or hardeners, reinforcements, core materials, adhesives, etc.) with their reference and the supplier's identification
- references of existing raw material type approval certificates
- raw material data sheets containing, in particular, the supplier's recommendations on storage and use.

5.2.2 Storage conditions

The storage conditions of raw materials are to be in accordance with the manufacturer's recommendations.

All the raw materials are to be identifiable in the storage site (product and batch references, type of approval certificates).

The builder is to provide an inspection to ensure that the incoming raw materials are in accordance with the purchase batches and that defective materials have been rejected.

The following details about storage conditions are to be submitted by the shipyard to the Society:

- identification of storage site on yard lay-out plan (specifying all the separated storage sites and those equipped with ventilation and/or air conditioning system)
- storage conditions:
  - summer maximum temperature and relative humidity
  - winter minimum temperature and relative humidity
- temperature and hygrometry monitoring (i.e. recording)
- keeping and presence of logbook (e.g. consignment number, dates) for inventory control.

5.2.3 Preparation of raw materials

The following details about raw material preparation are to be submitted by the shipyard to the Society:

- Resins and gel-coats
  - identification of preparation unit on lay-out plan
  - manufacturer's specifications and recommendations
  - resin blend in method and preparation procedure
  - accompanying data sheets
- Reinforcement fabrics and core materials
  - identification of preparation area on lay-out plan
  - preparation procedure
  - accompanying data sheets.

- Gel-coating unit
  - locations with details of means of separation from other workshops
  - equipment in gel-coating units: air conditioning, ventilation, dust extraction
  - hygrometry and temperature monitoring: number of hygrometers/thermometers, positioning, recording and height about ground level
  - laying procedure
  - moulds: type of mould, storage of moulds, preparation procedure (e.g. heating, cleaning, waxing)
  - accompanying data sheets.

5.2.4 Traceability of raw materials

The following information on raw material traceability are to be registered by the shipyard during hull construction:

- For gel-coats, resins and adhesives:
  - amount of the various components necessary to prepare the resin systems in relation to the temperature in the laminating unit
  - batch reference, date and time of laminating
- For reinforcement fabrics:
  - precautions taken to prevent condensation caused by the temperature difference
  - identification of reinforcement fabrics and location in the hull
  - batch reference, date and time of laminating
- For core materials:
  - precautions taken to prevent condensation, to avoid gather dust and to reduce the amount of gazing
  - identification of core materials and adhesives used for laminating
  - batch reference, date and time of laminating.

5.3 Laminating procedures

5.3.1 Laminating process

The following information on the different stages of the laminating process are to be registered by the shipyard during hull construction:

- date and time of the operation
- temperature and hygrometry during the operation
- reference of raw materials used
- reference of laminating drawings used
- directions of reinforcement fabrics
- bubble elimination operation
- preparation of the laminated zone intended for subsequent re-laminating or gluing.

The following assembly process is to be registered, on the same bases as for stages of laminating process:

- installation of internal structural components such as bulkheads, stiffeners
- connection between hull and deck.

5.4 Non Destructive Testing (NDT)

5.4.1 Application

The non-destructive testing, their extent and their result acceptance criteria are to be defined by the shipyard are to be submitted to the Society for information.

The non destructive testing processes may be:

- ultra-sonic testing
- spectroscopy
- differential scanning calorimetry (DSC)
- radiography.

5.5 Tank and weathertight structure testing

5.5.1 General

The pressure testing conditions for tanks, watertight and weathertight structures in order to check the tightness and/or the strength of structural elements are defined in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2]).

As a rule, these tests are to be carried out for ships surveyed by the Society during construction within the scope of classification.

6 Survey for unit production

6.1 General

6.1.1 The survey for unit production includes the following steps:

- survey at yard with regard to the requirements defined in Article [5]
- structure drawing examination as defined in Article [3]
- survey at yard during unit production with regard to approved drawings, yard's response to comments made by the Society during structure review examination and construction requirements.

These steps allow only to focus on the construction stage in progress during survey. It is to the responsibility of the inspection department of the yard to present to the Surveyor any defects noted during the construction of the ship.

7 Alternative survey scheme for production in large series

7.1 General

7.1.1 Where the hull construction is made in large series, an alternative survey scheme may be agreed with the Society for hull to be surveyed as far as classification is concerned, or hull to be certified by the Society on voluntary basis.

7.1.2 The general requirements for the alternative survey scheme, BV Mode I, are given in NR320 Certification Scheme of Materials & Equipment, as amended.

7.1.3 The alternative survey scheme comprises the following steps:

- type approval
- yard's recognition based on initial audit and periodical audits
- certificate of conformity issued by the yard and submitted to the Society for endorsement.

7.2 Type approval

7.2.1 General

The type approval of a hull made of composite materials, plywood or HDPE and built in large series comprises:

- examination, in accordance with the present Rule Note and the Rules for the classification of ships (see Sec 1, [1.1.2]), of drawings and documents defining the main structural components of the hull and the raw materials
- mechanical tests on laminate test panels
- examination of certain items of equipment and their fittings if requested by the Rules for the classification of ships (see Sec 1, [1.1.2])
- inspection of the first hull (or a hull representing the large series production).

7.2.2 Examination of drawings

The structure drawing examination is to be carried out as defined in Article [3].

The raw materials are to be in compliance with Article [2].

7.2.3 Mechanical tests on laminate test panels

Mechanical tests on laminate test panels, representative of the construction of the hull, are to be carried out as defined in Article [4].

7.2.4 Examination of certain items of equipment

The equipment requiring a particular drawing examination is defined in the Rules for the classification of ships (see Sec 1, [1.1.2]). As a general rule, this equipment consists mainly in portholes, deck hatches and doors.

This examination may be carried out as defined in the Society's Rules or through an homologation process, at the satisfaction of the Society.

7.2.5 Survey

The purpose of the survey, carried out by a Surveyor of the Society according to [5] on the initial hull (or a representative hull) of the series, is to make surveys at yard during unit production with regard to approved drawings, yard's response to comments made by the Society during structure review examination and construction requirements.

7.2.6 Type approval certificate (TAC)

A type approval certificate is issued for the initial hull covered by the type approval procedure.

7.3 Quality system documentation

7.3.1 The quality system documentation submitted to the Society is to include the information required in [5.1] and in NR320 Certification Scheme of Materials & Equipment, as amended.

7.4 Manufacturing, testing and inspection plan (MTI plan)

7.4.1 For each type of hull, the manufacturing, testing and inspection plan is to detail, specifically, the following information:

a) Raw materials

- Reference:
  - Exhaustive list of all the main raw materials used in the composite hull manufacture and covered by the Rules for the classification of ships (see Sec 1, [1.1.2])

Note 1: The main raw materials comprise gel coats, resin systems, fibre fabrics, core materials and structural adhesives.

  - For each main raw material, information such as maker's name, product reference, product homologation reference (specifying the date of validity of the type approval certificate)
  - Special requirements from the supplier, such as storage temperatures and hygrometry, maximum shelf life of product, type of checks to be performed on incoming products and properties to be tested by the yard before use, same checks and test to re-qualify outdated products
- Storage conditions:

  Information on storage sites (location of storage site in relation to lamination units, stating variations of temperature and hygrometry, ventilation conditions, supplier data sheets specifying the storage conditions, measures to be taken if irregularities occur during storage, listing documents to record arrival and departure dates for consignment)
- Reception:

  Information on consignment (traceability of consignment specifying date of arrival, type of inspection, check on product packaging, types of specific tests performed)
- Supply of raw materials to lamination units:

  Description of conditions and precautions taken, when preparing each raw material for use, to avoid wide temperature variations before use, and methods adopted to prevent use of outdated products
- Traceability:

  Description of the yard process to ensure traceability of the raw materials from the time of reception to the end of the production operations.

b) Preparation for raw materials

- Gel coats and resins:

  Method for checking, before preparation, that the technical components of the resin systems have been stored in accordance with the suppliers' and the yard's procedures, method and equipment used to measure the various components, in particular in relation to the temperature in the lamination unit
- Fibre fabrics:

  Identification, inspection and cutting processes, precautions taken to prevent condensation caused by the temperature variations when cutting operation is not done in the lamination unit, process ensuring traceability of fabric batches after preparation
- Core materials for sandwich:

  Same information as for the fibre fabrics and precautions taken to avoid dust in the core materials, in particular for nomex types
- Adhesives:

  Same information as for the resin systems and suppliers' stipulations on the maximum time elapsing between preparation and application of adhesives.

c) Moulds for lamination

- Type of moulds:

  Mould used (materials, male or female, type -whole moulding or half-hull moulding-, bottom and/or deck countermould) and means of storage
- Preparation of mould:

  Precautions taken to prevent condensation caused by temperature variations between the storage site and mould workshop, preparation description, compatibility and time lapses to be observed between applications of the stripping agent and the gel-coat
- Dimensional tolerances:

  Dimensional tolerances between mould and countermould, when used.

d) Lamination operations

- Lamination environment:

  Minimum and maximum temperatures and hygrometry for lamination operations, means of measuring these data, procedures to alter the lamination process when the temperature and hygrometry readings exceed limits, precautions taken to prevent presence of dust during lamination operations

- Lamination process:
  - Process of application of gel coat (spraying installation, conditions of supplying raw materials during gel coating operations ensuring a chemically homogeneous gel coat, thickness to be applied and means to measure it, thickness tolerances and inspection procedures carried out after gel-coating specifying the yard reference documents for common defects, stating causes and remedies)
  - Processes of laminating operations (time elapsing between the end of gel coating and application of the first laminate layer, process and sequences of laminating, method ensuring that arrangement of layers, resin content and thickness comply with drawings examined by the Society, maximum intended time between the successive applications of layers, preparation of laminated zones intended for subsequent re-lamination or gluing, placing of inserts)
  - Processes of application of core materials (time elapsing between application of core materials and the last lamination operation, process of application of core materials, bonding agent, precautions taken to ensure adherence between core and laminate and to ensure continuity between the various core panels, lay down of high density foam area, preparation of core surface for lamination of the second skin).

e) Hull construction

Description of the yard process to ensure that the scantlings and construction meet the rule requirements in relation to the approval drawings.

f) Hull/deck connection

Information on the main operations of connection of hull with deck (preparation of surface to be bonded, products used, means of ensuring contact pressure).

g) Installation of internal structure

- Information on the main operations of installation of internal structure and/or countermould (time elapsing between hull lamination and countermould fitting, characteristics of products used for assembly, means for ensuring contact pressure and immobility of components during polymerisation)
- Lamination of bulkheads and stiffeners (time elapsing between lamination of hull and fitting of bulkheads and stiffeners, type of local laminate preparation for lamination of bulkheads and stiffeners, product used for lamination).

h) Test panel during series production

In addition to the mechanical tests on laminate test panels requested for the type-approved hull as defined in [7.2], mechanical tests on panels may be requested by the Society at regular intervals during the series production of hulls.

The frequency and the type of the mechanical tests to be carried out is to be at the satisfaction of the Society.

i) Equipment

- References:

  Equipment references, references to any homologation of the equipment, suppliers' technical requirements, precautions taken during installation of the equipment, scheduled tests and traceability on equipment upon arrival and/or after installation
- Precautions for installation:

  Precautions taken to comply with requirements of both the suppliers and the Society, in order not to cause, during installation, structure damages able to affect structural strength and watertightness, and preparations to be made on the hull for the purpose of installation.

Note 2: The main equipment to be covered by the Rules of the Society is, as a general rule, portholes, windows, deck hatches, watertight doors, rudders and, in addition for yachts, chain plate and means of attachment of the solid keel.

j) Testing and damage reference documents

Information on tests and inspections performed, acceptance criteria and means of handling non-conformities.

7.5 Society's certificate

7.5.1 Certificate of recognition

After completion of the examination, by the Society, of the quality assurance manual, the MTI plan and the yard audit, a Certificate of recognition may be granted as per the provisions of NR320 Certification Scheme of Materials & Equipment, as amended.

7.5.2 Certificate of conformity

Each hull may be certified individually upon request made to the Society.

7.6 Other certification scheme for production in large series

7.6.1 Other certification scheme for production in large series, based on NR320 Classification Scheme of Materials & Equipment may be considered by the Society on a case by case basis.

Appendix 1 Raw Material Homologation Procedure

1 General

1.1 Application

1.1.1 The purpose of this Appendix is to give the procedure to be followed by the Manufacturer for the homologation of raw materials used in the construction of hulls built in composite materials within the scope of classification and/or certification.

These procedures are intended to verify the compliance of the raw materials with the relevant hull structure requirements of the Society.

The general requirements for the certification scheme of materials are given in NR320 Certification Scheme of Materials & Equipment, as amended.

Procedures for raw materials not explicitly included in this Appendix are subject to special examination by the Society.

1.1.2 As a rule, the principal raw materials to be submitted to an homologation program are:

- gel-coats and resin systems
- reinforcement fabrics
- core materials for sandwich laminates
- adhesive.

1.1.3 Homologation program

As a general rule, raw materials manufactured in series correspond to HBV product within the scope of the certification scheme of materials as defined in NR320 Certification Scheme of Materials & Equipment.

The homologation process of raw materials requests the two following successive phases:

- Design type approval: To review the technical documentation and mechanical characteristics proposed by the supplier in compliance with the rule requirements (see Article [2])
- Work's recognition: To assess the compliance of the raw materials manufactured in series with the design type approval (see Article [3]).

1.1.4 Certificate and responsibilities of the Manufacturer

Upon satisfactory completion of the two phases, a type approval certificate and a recognition certificate are issued by the Society under conditions defined in NR320 Certification Scheme of Materials & Equipment.

A manufacturer's document stating the results of tests performed and/or stating compliance with the approve type is to be issued.

The Manufacturer is fully responsible for the quality of the finished raw materials and is to ensure compliance with the specified requirements.

2 Design type approval of raw materials

2.1 Approval test program

2.1.1 The review of the technical documentation and the type test program are to be carried out as defined in NR320 Certification Scheme of Materials & Equipment.

The test program, drawn up jointly by the supplier and the Society, as well as the minimum required mechanical test results, may be as defined in Tab 1.

Some tests may be dropped from this list, and other additional tests requested, depending on the particular use, or experience acquired, with the materials under approval test program.

Technical reports, issued in the forms stipulated in standards indicated in Tab 1, are to be submitted to the Society for examination.

2.2 Work's recognition

2.2.1 The general requirements for the work's recognition schemes are given in NR320 Certification Scheme of Materials & Equipment.

Table 1 : Typical approval tests for raw materials

Raw material	Property / Characteristics		Required value	Recommended test method / Required value
Polyester gel coat (cured) **(1)**	Tensile	modulus (N/mm^2)	≥ 3000	ISO 527 or equivalent**(2)**
		elongation at break (%)	≥ 2,5	
	Water absorption (mg) over 28 days		≤ 80	ISO 62 Method 1 or equivalent**(3)**
Resin systems **(1)**	Density		Manufacturer nominal value ± 1%	ISO 1183 or equivalent
	Tensile	modulus (N/mm^2)	≥ 85% of the values given in Sec 4, Tab 1	ISO 527 or equivalent**(2)**
		elongation at break (%)		
	Glass transition temperature		≥ to Manufacturer value	ISO 11357 or equivalent
Adhesive **(11)** **(12)**	Tensile	modulus (N/mm^2)	Manufacturer nominal value ± 10%	ISO 527 ASTM D 638
		elongation at break (%)		
	Shear	modulus (N/mm^2)	Manufacturer nominal value ± 10%	ISO 11003-2 ASTM D 3983 NF EN 14869-2
		elongation at break (%)		
	Glass transition temperature		≥ to Manufacturer value	ISO 11357 or equivalent
Yarn	Weight per unit of length (tex)		Manufacturer nominal value ± 10%	ISO 1889 or equivalent **(4)**
Chopped strand mat	Weight per unit of area (g/m^2)		Manufacturer nominal value ± 10%	ISO 3374 or equivalent **(5)**
	Tensile tests on laminate	modulus (N/mm^2)	as per the present Rules	ISO 3268 or equivalent
		elongation at break (%)		
Woven roving and unidirectional	Weight per unit of area (g/m^2)		Manufacturer's nominal value ± 10%	ISO 4605 or equivalent **(6)**
	Tensile tests on laminate	modulus (N/mm^2)	as per the present Rules	ISO 3268 or equivalent **(7)**
		elongation at break (%)		
Pre-preg	Percentage of reinforcements in mass (%)		Manufacturer's nominal value ± 5%	ISO 1172 or equivalent **(6)**
	Weight per unit of area (g/m^2)		Manufacturer's nominal value ± 5%	ISO 10352 or equivalent **(6)**
	Tensile tests on laminate	modulus (N/mm^2)	as per the present Rules	ISO 3268 or equivalent **(7)**
		elongation at break (%)		
	Determination of glass transition temperature		Manufacturer's nominal value ± 5%	ISO 11357-2 or equivalent **(1)**
Foam for sandwich (for core structural use) **(9)**	Density (kg/m^3)		Manufacturer's nominal value ± 5%	ISO 845 or equivalent **(8)**
	Tensile modulus (N/mm^2)		Manufacturer's nominal value ± 5%	ISO 1926 or equivalent
	Shear	modulus (N/mm^2)	≥ 85% of the values given in Sec 4, Tab 3	ISO 1922 or equivalent
		ultimate strength (N/mm^2)		
	Water absorption (% in volume for 7 days)		≤ 2,5%	ISO 2896 or equivalent **(10)**
	Styrene resistance (when applicable)	dimensional control	≤ 2%	ISO 175 or equivalent**(8)**
		mass control		

Raw material	Property / Characteristics		Required value	Recommended test method / Required value
Balsa wood for sandwich (end grain)	Density (kg/m^3)		Manufacturer's nominal value ± 5%	ISO 3131 or equivalent
	Tensile modulus (N/mm^2)		≥ 85% of the value given in Sec 4, Tab 4	ISO 3345 or equivalent
	Shear	modulus (N/mm^2)	≥ 85% of the values given in Sec 4, Tab 4	ISO 8905 or equivalent
		ultimate strength (N/mm^2)		

(1) Curing process of the samples to be specified by the Manufacturer.
(2) Length of sample: 150 mm.
(3) Distilled water at 23° C. Circular sample of 50 mm diameter and 3 mm thickness.
(4) Three samples of 1 m length.
(5) Six samples 300 mm x 300 mm.
(6) Three samples 300 mm x 300 mm.
(7) Tensile tests are to be carried out in the two main directions of reinforcement. To test fabrics other than pre-preg, samples are to be made with a resin of an approved type. As a rule, samples are to be made with at least three layers of the fabric to be approved. Measurements of percentage of reinforcement in mass are to be carried out on samples submitted to tensile test.
(8) Three samples 100 mm x 100 mm x plate thickness.
(9) It may be requested, for foam used in sandwich panel cured with a heat process, that test foam samples be subjected to the same heat process before the test.
(10) Three samples 150 mm x 150 mm x thickness (minimum volume = 500 cm^3 per sample).
(11) Curing process and material of sample pieces to be specified by the Manufacturer.
(12) Tests may be requested at different temperature range (see Sec 4, [5.2.3]).

3 Equivalent raw material homologation process

3.1 General

3.1.1 On a case-by-case basis and particularly when raw materials used for composite hull are known by the Society (type of raw material and supplier, previous homologation), mechanical test on laminate panel as defined in Sec 12, [4] and possibly specific mechanical tests on raw materials may be considered as equivalent to the raw material homologation process.

Appendix 2 Buckling Analysis for High Density Polyethylene (HDPE) Structure

Symbols

a : Length of the longer side of the plate panel, in mm

α : Aspect ratio of the plate panel, to be taken as:

$$\alpha = \frac{a}{b}$$

b : Length of the shorter side of the plate panel, in mm

E : Young's modulus, in N/mm²

ν : Poisson's ratio of the material

R : Tensile strength at yield, in MPa

σ_x : Stress applied on the shorter side b of the plate panel

σ_y : Stress applied on the longer side a of the plate panel

σ_E : Elastic buckling reference stress, in N/mm², to be taken as:

$$\sigma_E = \frac{\pi^2 E}{12(1-\nu^2)}\left(\frac{t_p}{b}\right)^2$$

s : Spacing, in m, between stiffeners.

τ : Applied shear stress, in N/mm²

t_p : Thickness, in mm, of the plating considered

1 General

1.1 Application

1.1.1 The requirements of this Appendix apply for the buckling check of plate in HDPE material subjected to compression and shear stresses induced by overall bending moment and shear forces due to global hull girder loads (see [2.3] and [2.4]).

Note 1: When the plate is submitted to local compression loads, the buckling check may be carried out taking into account the compression stress applied to the plate induced by local loads and requirements defined in [2.3] and [2.4].

2 Buckling analysis for plating

2.1 Calculation hypothesis

2.1.1 General

a) The buckling approach defined in the present Appendix is based on the NR615 Buckling Assessment of Plated Structures, taking into account the following simplifying hypothesis:

- the applied compression stress is considered as uniform along the edges of the plate (the edge ratio Ψ according to NR615 is taken equal to 1)

Note 1: When the applied compression stress along the edges of the plate is not uniform (ratio Ψ different from 1), the applied stress to consider in the present Appendix is to be taken equal to the maximum applied compression stress along the edge

- when the buckling check is carried out with bi-axial compression hypothesis, the stresses σ_x and σ_y are as a general rule determined by finite element calculation or direct calculation.

Note 2: When the compression stress applied on the edge not directly loaded by the global loads is not determined by FEM or direct calculation, this compression stress may be considered as null.

- plate panels are considered as being simply supported on their edges.

b) The buckling approach defined in NR615 Buckling Assessment of Plated Structures may be taken into account instead of the present simplify method when deemed necessary.

2.2 Sign convention for normal stresses

2.2.1 In the present Appendix, compression and shear stresses are to be taken as positive.

Tensile stresses are to be taken as negative.

2.3 Critical stress under buckling

2.3.1 Critical buckling stress by compression of the shorter edge of the panel

The ultimate buckling stress of plate panels, in N/mm², induced by compression of the shorter edge of panel, according to Fig 1, is to be taken as:

$\sigma_{cx}' = C_x R$

where:

C_x : Coefficient equal to

$C_x = 1,00$ for $\lambda \le 0,84$

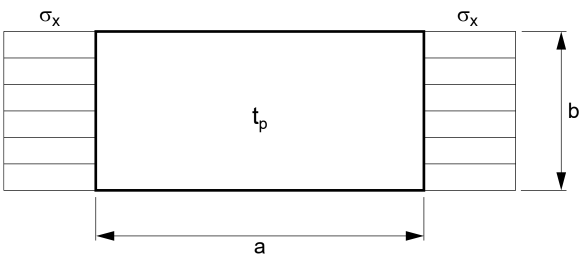
$$C_x = 1,13\left(\frac{1}{\lambda} - \frac{0,22}{\lambda^2}\right) \text{ for } \lambda > 0,84$$

λ : Reference degree of slenderness, to be taken as:

$$\lambda = \sqrt{\frac{R}{K_x \sigma_E}}$$

K_x : Buckling factor equal to 4

Figure 1 : Compression on the shorter edge of the panel



2.3.2 Critical buckling stress by compression of the longer edge of the panel

The ultimate buckling stress of plate panel, in N/mm², induced by compression of the longer edge of panel, according to Fig 2 is to be taken as:

$\sigma_{cy}' = C_y R$

where:

$$C_y = 1,13\left[\frac{1}{\lambda} - \frac{S + F^2(H - S)}{\lambda^2}\right]$$

λ : Reference degree of slenderness, to be taken as:

$$\lambda = \sqrt{\frac{R}{K_y \sigma_E}}$$

$$K_y = \left(1 + \frac{1}{\alpha^2}\right)^2$$

S : Coefficient equal to:

$S = 0,22$ for $\lambda \ge 0,84$

$$S = \lambda\left(1 - \frac{\lambda}{1,13}\right) \text{ for } \lambda < 0,84$$

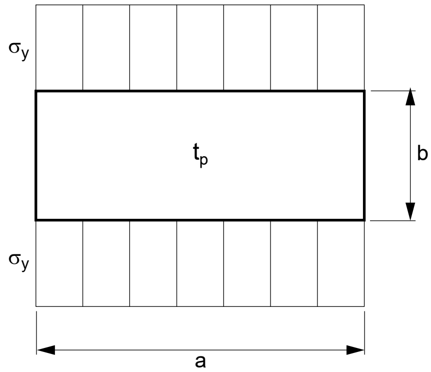
$$F = 1 - \frac{\left(\frac{K_y}{0,91} - 1\right)}{\lambda_p^2} \ge 0$$

$$\lambda_p^2 = \lambda^2 - 0,5 \text{ with } 1 \le \lambda_p^2 \le 3$$

$$H = \lambda - \frac{2\lambda}{1,13\left(T + \sqrt{T^2 - 4}\right)} \ge S$$

$$T = \lambda + \frac{14}{15\lambda} + \frac{1}{3}$$

Figure 2 : Compression of the longer edge of the panel



2.3.3 Critical shear buckling stress

The ultimate shear buckling stress of plate panels, in N/mm², according to Fig 3 is to be taken as:

$$\tau_c' = C_\tau \frac{R}{\sqrt{3}}$$

where:

C_τ : Coefficient equals to:

$$C_\tau = 1,00 \text{ for } \lambda \le 0,84$$

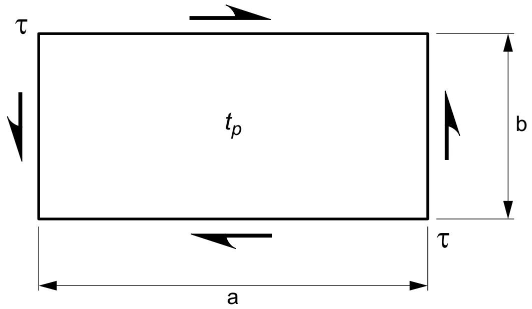
$$C_\tau = \frac{0,84}{\lambda} \text{ for } \lambda > 0,84$$

λ : Reference degree of slenderness, to be taken as:

$$\lambda = \sqrt{\frac{R}{K_t \sigma_E}}$$

$$K_\tau = \sqrt{3}\left(5,34 + \frac{4}{\alpha^2}\right)$$

Figure 3 : Shear stress



2.4 Buckling check criteria

2.4.1 General

The buckling strength or capacity defined in the present Article takes into account the internal redistribution of loads depending on the load situation, slenderness and type of structure.

2.4.2 Scantling criteria

The plate scantling is to fulfill the following conditions:

- $$\left(\left(\frac{\sigma_x SF}{\sigma_{cx}'}\right)^{e_0} + \left(\frac{\sigma_y SF}{\sigma_{cy}'}\right)^{e_0} + \left(\frac{|\tau| SF}{\tau_c'}\right)^{e_0} - \Omega\right) \le 1$$

  with:

  $$\Omega = B\left(\frac{\sigma_x SF}{\sigma_{cx}'}\right)^{e_0/2}\left(\frac{\sigma_y SF}{\sigma_{cy}'}\right)^{e_0/2}$$

- when $\sigma_x \ge 0$ (compressive)

  $$\left(\left(\frac{\sigma_x SF}{\sigma_{cx}'}\right)^{2/\beta_p^{0,25}} + \left(\frac{|\tau| SF}{\tau_c'}\right)^{2/\beta_p^{0,25}}\right) \le 1$$

- when $\sigma_y \geq 0$ (compressive)

$$\left(\left(\frac{\sigma_y\ SF}{\sigma_{cy}'}\right)^{2/\beta_p^{0,25}} + \left(\frac{|\tau|\ SF}{\tau_c'}\right)^{2/\beta_p^{0,25}}\right) \leq 1$$

- $\left(\frac{|\tau|\ SF}{\tau_c'}\right) \leq 1$

where:

σ_x, σ_y : Actual normal stresses applied on the plate panel, in N/mm², respectively in the shorter edge and the longer edge of the panel, taking into account the sign convention for normal stresses defined in [2.2]

τ : Actual shear stress applied on the plate panel, in N/mm², taking into account the sign convention for normal stresses defined in [2.2]

σ_{cx}' : Ultimate buckling stress, in N/mm², in the shorter edge of the panel, as defined in [2.3.1]

σ_{cy}' : Ultimate buckling stress, in N/mm², in the longer edge of the buckling panel, as defined in [2.3.2]

τ_c' : Ultimate buckling shear stresses, in N/mm², as defined in [2.3.3]

SF : Safety buckling factor SF_{buck} defined in the Society Rules for the classification and/or certification of ships (see Sec 1, [1.1.2])

B, e_0 : As defined in Tab 1

Table 1 : Coefficients B and e_0

Applied stresses	B	e_0
$\sigma_x \geq 0$ and $\sigma_y \geq 0$	$0,7 - 0,3\ \beta_p / \alpha^2$	$2/\beta_p^{0,25}$
$\sigma_x < 0$ or $\sigma_y < 0$	1,0	2,0

Note 1:
β_p : Plate slenderness parameter taken as:

$$\beta_p = \frac{b}{t_p}\sqrt{\frac{R}{E}}$$

2.4.3 Plate capacity

For information, the plate limit state is based on the following interaction formula:

- $$\left(\left(\frac{\gamma_{c1}\ \sigma_x\ SF}{\sigma_{cx}'}\right)^{e_0} + \left(\frac{\gamma_{c1}\ \sigma_y\ SF}{\sigma_{cy}'}\right)^{e_0} + \left(\frac{\gamma_{c1}\ |\tau|\ SF}{\tau_c'}\right)^{e_0} - \Omega\right) = 1$$

- when $\sigma_x \geq 0$ (compressive)

$$\left(\left(\frac{\gamma_{c2}\ \sigma_x\ SF}{\sigma_{cx}'}\right)^{2/\beta_p^{0,25}} + \left(\frac{\gamma_{c2}\ |\tau|\ SF}{\tau_c'}\right)^{2/\beta_p^{0,25}}\right) = 1$$

- when $\sigma_y \geq 0$ (compressive)

$$\left(\left(\frac{\gamma_{c3}\ \sigma_y\ SF}{\sigma_{cy}'}\right)^{2/\beta_p^{0,25}} + \left(\frac{\gamma_{c3}\ |\tau|\ SF}{\tau_c'}\right)^{2/\beta_p^{0,25}}\right) = 1$$

- $\left(\frac{\gamma_{c4}\ |\tau|\ SF}{\tau_c'}\right) = 1$

where:

γ_c : Applied stress multiplier factor involving the plate buckling failure of the above different limit state

The stress multiplier factor as failure, γ_c, is taken as:

$\gamma_c = \text{Min}\ (\gamma_{c1}; \gamma_{c2}; \gamma_{c3}; \gamma_{c4})$

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